Systems-2020 Study

Final Report

Booz Allen Hamilton

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Table of Contents

I. Systems-2020: New Engineering Approach to Defense Systems

The United States (U.S.) faces a complex and uncertain security landscape in which the pace of change continues to accelerate. Changes include new foreign powers, non-state actors, and the availability of destructive enabling technologies[1].

Since the middle of the 20th century, Department of Defense (DoD) technological superiority has relied on the efficient development and applied capabilities of complex systems, based on proven systems engineering methods. As DoD systems grow and advance technologically, so too does their complexity, risk, and development time. During the Cold War, where the enemy and the threat were well understood, DoD development timelines for fielding and upgrading systems were acceptable; they are, as we shall see, not acceptable now.

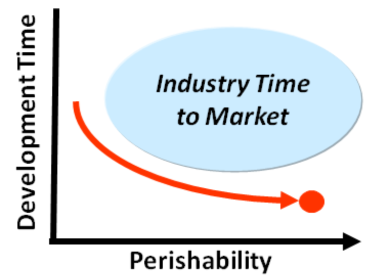

Figure 1: Industry Development and Endurance Timelines

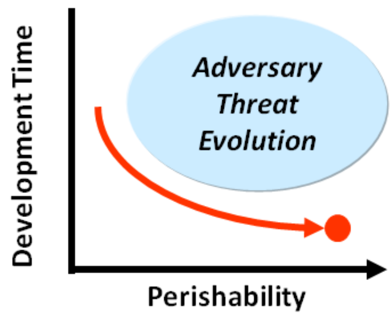

Figure 2: Adversary Counter Measure Timelines

The commercial sector has embraced with gusto the idea of rapidly leveraging the benefits of global technology. As a result, their development time has greatly decreased, as shown in Figure 1. Note that this development timeline has come at a price, fielded systems are increasingly perishable; both obsolescence *and* technology refresh rates are increasing. (We define *perishability* as the inverse of sustainability; that is perishability measures the speed upon which the utility of an unmodified system declines.)

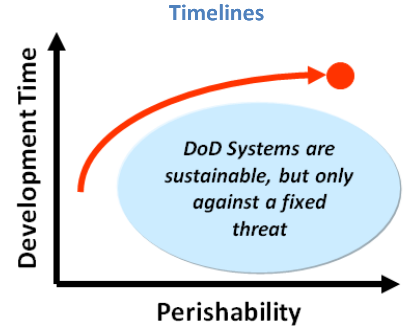

Figure 4: Defense Systems Perishability

Figure 3: We are faced increasingly with threats that are surmountable, but which are highly unpredictable

In this study, we identified tools, technologies, and approaches within industry and academia, that will allow the Department to mimic the rapid development timeline in Figure 1. While such an endeavor is laudable in and of itself (from a fiscal perspective) there is an urgent operational need to do so. Specifically *the emerging threat environment demands we enhance the speed in which we deliver new capabilities.* Indeed our adversaries, shamelessly and creatively leveraging commercial off the shelf (COTS) trends as per Figure 1, have already successfully accomplished this, as depicted in Figure 2. As DoD evolves, our enemy combatants are able to evolve faster, allowing them to develop counter measures faster than U.S. forces can develop counter-counter measures. This leads to an untenable pattern, shown in Figure 4, whereby both development time *and* perishability are increasing. In effect our acquisition style, designed for warfare during the Cold War, where the enemy and the threat were well understood, are ill-suited for fleeting,

[1] Quadrennial Defense Review Report. February 2010. Pg iii.

unpredictable threats. This shift in threat profile is depicted in Figure 3.

Figures 1-4 are, of course, notional. But they are well supported by evidence throughout this paper, through interviews, research, literature surveys, and commercial tool vendor inquiries. As a preliminary evidentiary step consider, Figure 5 which shows that with each passing technology adoption rate increases.

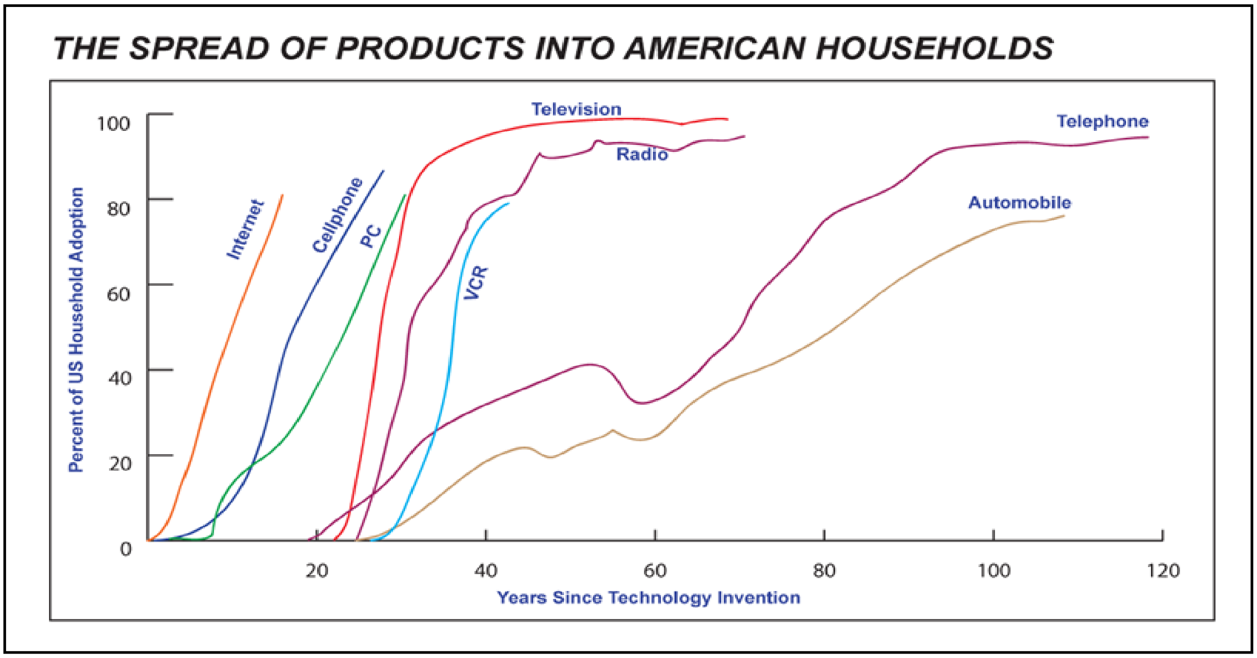

Figure 5: Technology adoption speed is increasing with each generation. It falls into our adversaries hands at a similarly accelerated rate.

The creation of technology *capabilities* is itself speeding up as well, as summarized in Figure 6 and Table 1. These figures and tables provide support for reduced timelines and perishability for commercial systems as shown in Figure 1. But what about the impacts of this technology acceleration on adversary capabilities (Figure 2) and the attendant effect U.S. systems (Figure 4)? Regrettably we have all too many examples of how our enemies are fielding results at rates faster than our own acquisition and fielding observe, orient, decide, and act (OODA) loop: see Figure 7.

Technology	Units	Date				Trend Origin	Comment
		1990	2000	2010	2020		
Data Generation	exabytes/months	0.0002	1	100	3000	IDC study (1)	exabyte= 100,000 x library of congress
Computer Power	MIPS/$1,000	0.01	1	300	1000	Moravec, CMU (2)	By 2020 compute power = human cognition
Internet Nodes	100M nodes	0.002	1	150	2000	IDC (3)	soon: more nodes than humans!
Wireless Bandwidth	10 conversations	0.1	1	400	4000	Edholm's law	10khz = human speech
Transistors/Chip	20 Million	0.05	1	250	1000	Moore's law	trend projected to continue with 3d fab
Digital Imagers	kilo-pixels/dollar	0.2	1	500	5000	Hendy's law	cell phones have accelerated the trend
1)	http://www.emc.com/collateral/demos/microsites/idc-digital-universe/iview.htm						
2)	http://www.mocom2020.com/2009/05/evolution-of-computer-capacity-and-costs/						
3)	http://www.idc.com/research/searchresults.jsp?sid=0						

Table 1: Comparison of technical capabilities verses year, in normalized units. Many technologies, not just computer chips are accelerating at an astonishing rate.

It is important to note that perishability is probably a permanent fixture in any viable technical solution to the canonical complex engineering challenges we face. That means that our defense systems will need to be reconfigurable post deployment. Why make these claims? First, recall that our force is an expeditionary force and will remain so as long as we retain a requirement for global access in defense of U.S. and our allies. This implies that we cannot simply reset our forces at the same pace as insurgents or even peer adversaries operating in home territories. As such, we will need systems that can survive for periods of time far in excess of the duration of any fixed but fleeting threat. This in turn requires systems built to adapt to threats not yet conceived of at the time of fielding. We conclude with an assertion.

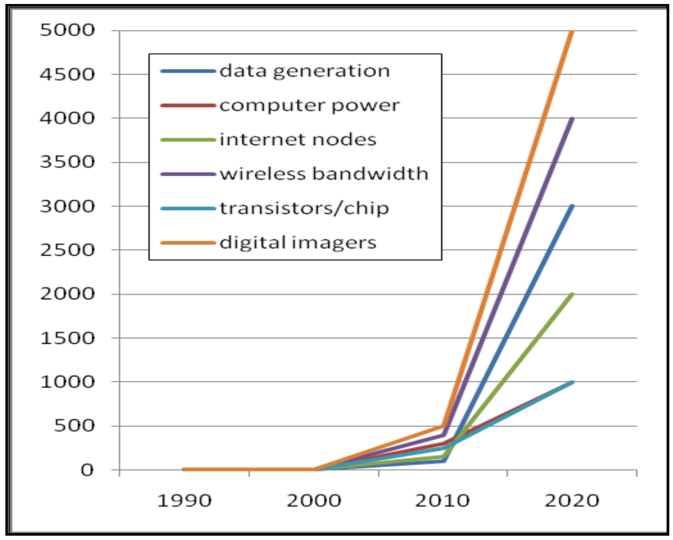

Figure 6: Growth in capability in various technologies as per Table 1. The units are normalized to year 2000 performance.

Systems-2020 Assertion: The uncertainty and unprecedented speed of technology development globally has led to a new paradigm for warfare. It virtually ensures solutions to military problems will be perishable. *This in turn requires the rapid development and fielding of systems capable of adapting post deployment.*

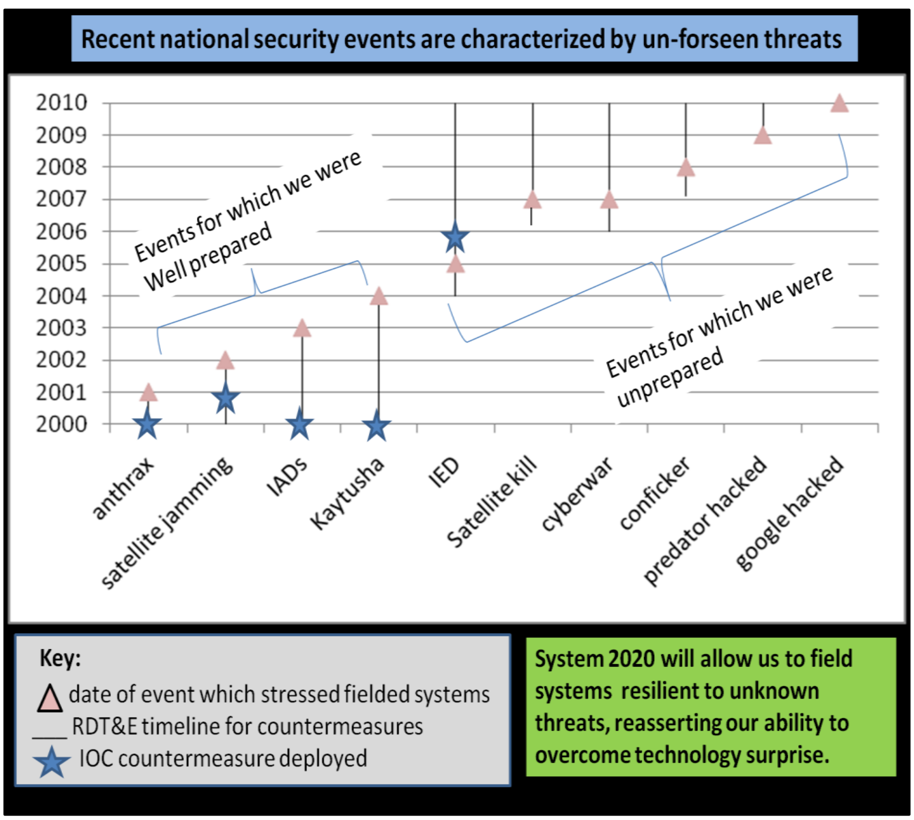

Figure 7: Timeline for recent attacks, or threats. Recent events (IED onward) occurred with little prior RDT&E, and our systems are now being modified after-the-fact to adapt. Appendix III, Table 3 contains more details behind these events.

The italicized words above form concisely the goal of Systems-2020. If in fact we achieve this goal what will it mean? How will we know we have succeeded? Perhaps this is best answered by looking at an example. We can turn to counter-IED technology. A System-2020 solution would be a fielded system that endured through many cycles of countermeasures. Such a system would be able to adapt to unseen changes with minimal infusion of new components and subsystems. In Figure 7, after Systems-2020, we would anticipate initial operational capability (IOC) deployments (stars in Figure 7) to appear at or near the timeline when a new threat is released.

Rapid development and fielding of systems capable of adapting post deployment seems like a daunting task, and perhaps even one that is hopelessly ill defined in the absence of a specified warfare domain. The following is a story of how we set about addressing this challenge.

II. Methodology

Any responsible parent can resonate with the challenge of "fielding of systems capable of adapting post deployment!" Indeed biology, by far, provides the best examples of systems able to adapt after deployment, whether we define deployment as birth (adapting under supervision), or adulthood (adapting unsupervised). While it may be entertaining to meditate on biological adaptation there is only one problem: we really have no clue whatsoever how biological adaptation *actually works!*

Therefore in this Study we set out to determine what makes adaptivity work in complex systems and what do we do to get it. We did this using a blend of literature surveys and interviews with theorists and practitioners. What we found was striking. Rather than a mosaic of conflicting views or theories we found the same recurring themes. In total, we surveyed 74 papers and interviewed 66 subject matter experts (SME). From this we compiled 65 tools and best practices/methodologies.

Appendix III contains excised narratives from our interviews. In these interviews we asked the following questions after defining the goal of System-2020:

1. What Technology/ Tool/ Approach are you aware of to assist in the development of new agile complex systems?
2. What Vendor/ Developer/ Thought Leader would you suggest we investigate or speak to for more information?
3. Describe the approach and its value.
4. What are the technical and non-technical challenges?

These interviews guided us to literature and web searches to obtain further details on the approaches discussed.

Through approximately 140 sources including interviews of industry and academic experts as well as literature examination, several over arching themes emerged repeatedly, the most salient being the following:

- **Define clear, relevant standards:**
    - For example the internet protocols allow every computer on the planet to communicate with every other computer. Similarly communications standards like 4G allow billions of devices to interact, and service oriented architecture (SOA) standards allow almost all data archives globally to interact.
- **Develop interfaces with the right amount of flexibility:**
    - Too much flexibility will add cost over the life cycle of a product. Too little, will lead to cost and time to upgrade. A good example of balanced flexibility is a modern phased-array radar, where solid design trades are used to balance flexibility (in scan agility, waveform diversity) and cost

(true time delay, number of analog to digital converters and radio frequency (RF) stages) using appropriate interfaces.

- **Seek Increased scalability:**
  - Sometimes referred to as a balanced hierarchy, design for scalability allows the system to embrace exponential technology growth. A good example of this balance lies in hierarchical control in avionics.
- **Increase pre-planned adaptability**
  - If one plans ahead to adapt one has much less retreading required in the field. Open architectures are an example of systems readily adaptable. A critical part of preplanned adaptation is providing embedded information about a system, so assumptions affecting adaptation are recoverable in the field.

Much of the above thinking is captured in the work of Joel Moses[2]. Dr. Moses takes the approach that complexity is inherent in systems exhibiting agility, but that the above organizational features can be used to assess whether or not complexity is properly contained for manageable operation and agility.

We can conveniently decompose enabling Systems-2020 technology into three bins:

- **Model-Based Engineering:** Leveraging modeling and simulation techniques to deal with the increasing complexity of systems.
- **Platform-Based Engineering:** Applying architectural and automated design tools to develop a system structure/platform that is based on commonality, as well as planned variability.
- **Capability on Demand:** Designing systems or services that enable an existing platform to adapt to evolving missions and user needs
- Each of these areas affects the others, together they build the standards, interfaces, hierarchies, and expandability required.

The remainder of the report describes each of these areas as it pertains to Systems-2020, describing state of the practice, state of the art, gaps, and recommendations, to include proposed pilot programs and research efforts. We will include a section of trusted systems, since robustness to exploitation attacks remains a concern for any fielded system.

III. Model-Based Engineering

A. Definition

Model-based engineering (MBE) is defined as leveraging modeling and simulation techniques to deal with the increasing complexity of systems. This approach facilitates the interaction of the different domains encountered in the concept creation-design-manufacturing cycle. Models can assist with all aspects of the complex system life cycle, from the interaction of stakeholders in an easy to use environment, to enabling the automatic interaction of sub-modules at different physical scales, to facilitating the manufacturing process as a network of services.

[2] Moses, Joel. *Towards a Science of Design*. MIT. Sep. 2003.

B. Findings

Current DoD system development is a linear process over a number of years. The length of the process drives technology stretch to meet distant future performance goals. The linearity of the current process involves many handoffs across organizational seams, inevitably with re-creation of data, miscommunication, errors, and late consideration of production potential and life-cycle attributes. Design decisions that were valid at one time may not be valid years later during production. The result is that the system that enters production too often encounters problems of low manufacturing yield, high cost, and multiple design changes. These problems increase with system complexity. The opportunity to achieve first pass success – i.e. to deliver a system that meets the operational need without scrap, rework and extensive design changes in production – requires both shortening the development timeline and eliminating or mediating the seams in the process.

With an understanding of the identified gaps and tools, technologies, and approaches outlined we found three core areas for improvement:

- Concept Engineering: Simulated user environments to explore design trades ("2nd life" for engineering)
- Virtual Design & Modeling: environments to design at a high level of abstraction ("compilers" for engineering)
- Model Driven Manufacturing: Emulating VHDL for semiconductors ("3D printers" for engineering)

The state of the art survey identified solutions that serve as case studies and are important existence proofs. But in general these solutions have been tailored to a particular company and product line of systems that are much less complex than DoD systems.

Figure 8 presents a high level view of the survey findings as lined up against the three promising areas of investment identified in the list above. Market sectors showing exemplary, state of the art solutions within an area are indicated in blue, sectors with common tool availability within an area are green, sectors with few or emerging capabilities are yellow, and sectors where no data was available are gray.

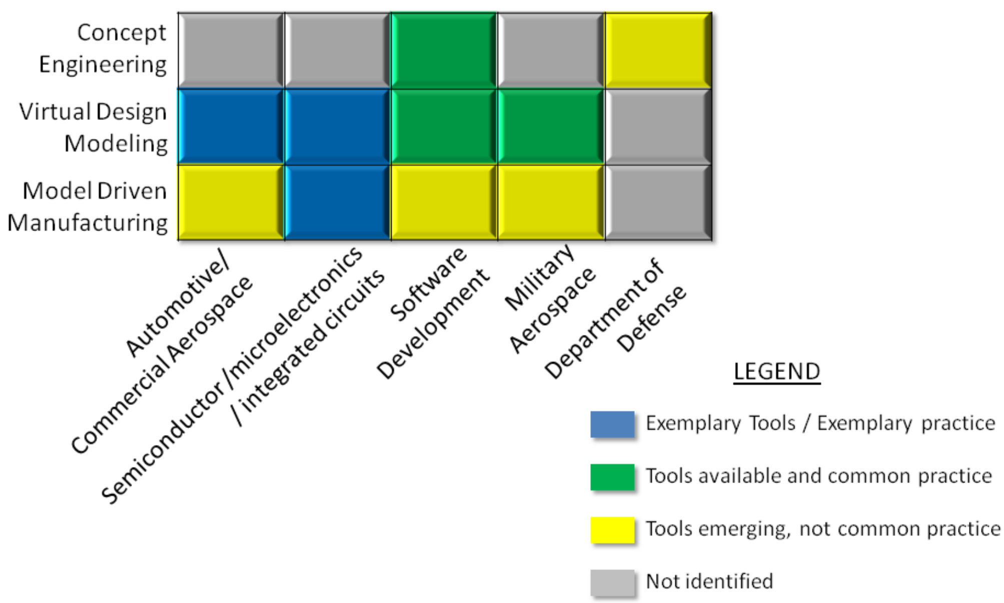

Figure 8: MBE Tool Summary

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Department's investment in high performance computing also provides new opportunities to realize the concept of a model-based virtual-system prototype from concept of operations (CONOPS) to manufacturing through the use of large scale computing resources.

1. Concept Engineering

Successful implementation of **concept engineering** will minimize the gaps in developing a new model as each linear hand-off takes place. By mitigating this gap, we will improve the ability to create collaboratively and interactively a model of the desired system behavior that can be used throughout the system life cycle resulting in the following:

- Accelerated **time to fielding** through:
  - ability to rapidly evaluate alternative concepts
  - improved communication with all stakeholders of the value proposition and intended operation of the system, something difficult to achieve otherwise in a timely fashion with a complex system.
  - avoidance of lengthy redesign cycles
- Increased **quality** through improved ability to:
  - support continuous system verification and validation throughout the lifecycle
  - train deployment, service and support personal earlier in life cycle
- Increased **flexibility** through ability to:
  - rapidly evaluate changing threats and explore the solution space
  - develop CONOPs to re-purpose existing/modified systems, as required for agility post fielding.

Investing in greater use of concept engineering within the Department has the potential to reduce the time to successful acquisition and fielding of weapon systems. Once fielded, due to the existence of a comprehensive previously developed model of the system, future unplanned and unforeseen mission requirements can be evaluated very quickly ranging from CONOPS to Manufacturing.

2. Virtual Design Modeling

An area where both DoD and industry are lacking is in the area of **cross domain tool development**. While not a specific idea within MBE, understanding of it within this context is important. The majority of current tools target a specific domain and user group with significant delineations between models even within a single technology or analytical program; while access to cross domain tool sets linking multiple systems or holistically modeling single systems from cradle to grave, is limited. Systematically, addressing the following cross domain areas will mitigate current gaps within the market and improve access across domain integrated solutions in the future:

- Environment for rapid evaluation of alternative concepts
  - Complex systems have unanticipated coupling between domains. For example, Doppler shifts from a satellite communication signal may have unintended consequences when this link is used in a new way as part of a larger network. Cross domain tools allow these "black swan" events to be exposed.
- Vehicles to validate the concept throughout the development lifecycle

- Rapid technology change (Figure 6) leads to modeling challenges post deployment. For example lithography feature size (which changes rapidly) has an unintended influence on vulnerability to pulsed weapons.
- Vehicles to perform trade analysis for upgrade options in subsequent versions of products
  - Adding new capabilities in one domain (Figure 6) invariably leads to impacts in others. This needs to be accounted for if surprise is to be avoided. For example faster processors, or improved self diagnostics, may consume more power reducing lifetime in unanticipated ways.

Research in these areas will apply tools and processes necessary to provide an efficient interactive environment so that diverse stakeholders groups can develop shared mental models beginning with the conceptual brainstorming process and carrying through to the development of a system CONOPS.

Cross domain MBE challenges are partly of a non-technical nature; getting the tool suppliers on board, encourage new tools providers, and gain buy-in from industry and MBE-related trade and standard organizations, such as IEEE. DoD, the major defense contractors, and their supply chain companies can play a key role through their support and engagement in the early pilots in not only maturing the MBE process but also engaging and encouraging the tool suppliers. Ultimately, in order to be successful, validation, verification, and accreditation, including trust, must be treated as first-class citizens throughout the MBE process.

3. Model Driven Manufacturing

The final area where significant gaps exist within MBE is within the **manufacturing community**. Within this community, there are areas both within the 6.1 (basic research) and 6.2 (applied research) where gaps are present. Within the 6.1 umbrella, basic research is required to understand the limits of modularity in structural and electromechanical systems, which differ in fundamental ways from the decoupled product and process architectures of VLSI[3]. Gaps within 6.2 consist of model driven process planning and control. These gaps include the following:

- **Multi-scale manufacturing** process modeling
- **Standards**, including ontologies, for product and process model interoperability and reuse

Successful model driven manufacturing services provide high impact results starting during design and test phases, and increasing during production and life cycle support. For example, when developing a new system, if during the design phase focus remained on a specific end product, the design and final validated process plans will already include considerations for the manufacturing of the system. In the microelectronics domain there is extensive experience with design rules[4] that decouple chip design from manufacturing and with semiconductor process simulation for new generations of semiconductor technologies. As a result, manufacturing development time reduces from multiple years to a predictable 18 month cycle for each technology node, making Moore's law possible[5]. The Intelligent Manufacturing Technology Initiative[6] reports "a ten-fold reduction in the response

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[3] Whitney, Daniel E. "Why Mechanical Design Cannot Be Like VLSI Design." http://esd.mit.edu/esd_books/whitney/whitney_online.html

[4] Conway, Lynn and Carver Mead. *Introduction to VLSI Systems.* Addison-Wesley. 1979.

[5] Sangiovanni-Vincentelli, Alberto. "Managing Complexity in IC Design." *Presentation to DARPA-NSF Complexity Workshop.* 2009.

[6] www.imti21.org/

time from requirements to complete manufacturing plan and a factor five times reduction in the cost and time of managing change are being documented"[7] by companies using early versions of manufacturing process simulation.

For defense systems, typically 70% of the manufacturing cost and time is associated with items from lower tier suppliers. Making product and process data available as a service can shorten the time for sub-tier suppliers to respond to both initial orders and changes.

C. Pilots and Research Efforts

Proofs of concept in many of these ideas have been implemented already in several applications and can be looked to for guidance when research and implementing other pilot studies or research efforts. For instance, Research Development and Engineering Command's (RDECOM) Mine Resistant Ambush Protected (MRAP) Expedient Armor Program (MEAP) and Boeing commercial aircraft development are examples of using virtual design modeling.

RDECOM's MEAP is a new requirement from in-theatre interactions. From intelligence in theatre, added protection was added to the MRAP. Modeling and Simulation tools provided a comprehensive understanding of alternatives regarding survivability, mobility, and dynamic ride. Use of these tools significantly reduced the time to deployment from months to two weeks. The same or similar principles were used in the development of the Boeing commercial aircraft.

Another example is the DoD ManTech program. It demonstrated a substantial increase in competition and decrease in response time by providing process data in addition to product data. The ManTech demonstration on a M2 machine gun part showed that an enhanced digital technical data package enabled suppliers to reduce the time required to interpret data and generate process plans, resulting in multiple competitive bids where there had previously been no bidders, and reducing time to delivery by 59%.[8] Moving beyond data as a service at the DoD and prime contractor level to a full set of manufacturing services can have even larger benefits. The Electronics Services Manufacturing sector has a number of commercial firms that provide design, manufacturing, and order fulfillment services. In 2005 DoD used such a service oriented firm to produce an improvised explosive device (IED) jammer called Warlock Blue. The result, 8,000 units were delivered in 54 days, compared to an estimate of 240 days from a traditional defense supplier. A change to the Warlock Blue order requiring addition of an antenna was handled with no delay in delivery.

In order to support the recommendations of the Systems-2020 study several pilot studies and research efforts are outlined for additional consideration:

- **Ground Vehicle**: U.S. Army's Tank Automotive Research, Development and Engineering Center (TARDEC) offers several pilot opportunities from theater driven upgrades, like the MRAP vehicles, to new ground vehicle developments (Joint Light Tactical Vehicle (JLTV) and ground combat vehicle (GCV)). Suggested flow would be to start with an upgrade pilot and then migrated to subsystem and finally to full system MBE pilot as the Systems-2020 technology and tools mature. **Pilot owner:** Army though TARDEC

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[7] *IMTI Update.* Winter 2010 Edition. www.imti21.org/newsletter/winter2010/model.html
[8] Ratcliff, Adele. Briefing to DDR&E Rapid Capabilities Toolbox Study. 3 Sep 2009.

- **Missile**: Since missiles are well defined systems with a lower degree of complexity than aircrafts they are a natural candidate for MBE research. This research would focus on the integration of all the components (operations, performance analysis, product design, process design, manufacturing analysis, supportability) from a stakeholder point of view (integration of the disks). **Research partner:** Raytheon Missile Systems
- **JET Engine**: Jet engines provide a unique opportunity for a creation of a research area. A jet engine pilot would explore how far one can model a very sophisticated product with very complex cold and hot section physics requiring multi-physics/multi-scale simulations at high levels of fidelity. **Research partner:** Pratt & Whitney

IV. Platform-Based Engineering

A. Definition

Platform-based engineering (PBE) is defined as applying architectural and automated design tools to develop a system structure/platform that is based on commonality, as well as planned variability. With this understanding, as part of the Systems-2020 study, several key characteristics of platforms and PBE were identified throughout our research. These characteristics as well as the definition of PBE create the basic qualification for inclusion within this survey. The key characteristics identified for PBE are as follows:

- Design platforms that are **reusable**
  - Reuse can take on many fashions. The designs can be as simple as designing a system where the screws are common throughout the system. Or it can be as complex as using the same satellite structure for multiple satellites of different purposes instead of starting from scratch for each satellite.

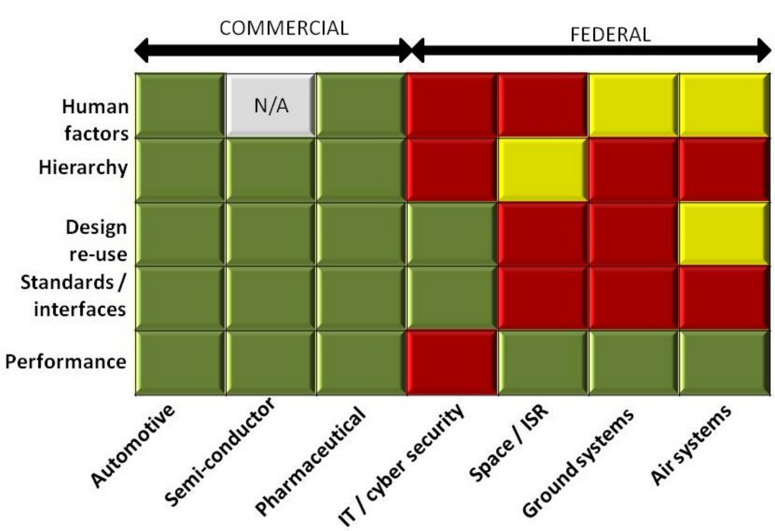

Figure 9: Platform Adaptability Assessment. Human factors include training and consistency of performance. So for example in IT and ISR variability in OPSEC and reporting styles greatly compound security and fusion challenges. In contrast human interfaces in military aircraft are robust as is the training regime.

- Design platforms that are **reconfigurable**
  - These platforms can change on a mission-by-mission, day-by-day, or war-by-war basis, just as a field programmable gate array (FPGA) can change based on the needs of the day.
- Design platforms that are **extensible** (Modified by changing or adding features)
  - A perfect example of this would be the HMMWV. It was designed as a tactical field vehicle; however during Operations Iraqi Freedom it took on new features, such as up-armoring and sensors to protect warfighters from IEDs.
- Platforms having well-defined

standards for both structure and interfaces

- Use of standard interfaces and structure promote the characteristic of reusability. Without standards, we cannot maximize our reuse. Therefore, using the example of the satellite structure again, satellite development can be improved by using standard interfaces for the sensors installed on the satellite bus. This allows for more adaptability within the system.

B. Findings

In order to assess the critical gaps within PBE, during the study, an assessment of how adaptable systems were, within both DoD and the commercial market place. Figure 9 depicts the current adaptability assessment as found through the research and survey of SMEs within the fields. **A key gap recognized during research and showcased here is that DoD does not develop product line architectures** (PLA) effectively. Industries such as the automotive, semi-conductor, and pharmaceutical industries have several methodologies that allow them to quickly develop products, PLAs is one of them. Not all systems used by DoD are appropriate for developing a PLA, but there are significant enough ones where PLAs are a recognized gap currently within the Department as guided by both research and experts within this field. In order to overcome some of these gaps research in the areas of architectural patterns, software product line techniques, intelligent design techniques, and open systems architectures, can be expected to play a crucial role in overcoming these barriers and will be discussed in greater detail in the following section.

Through our research we believe we identified some significant gaps with current system development within the area of PBE. To close these gaps, there are several approaches that may be taken. PLAs are frameworks for developing customer-specific applications in a particular domain and fit well into this philosophy of a product lifecycle. As mentioned previously, PLAs can help the Department benefit by promoting product lines when creating new systems. For instance, companies like Moen do not need to know the exact model of kitchen faucet your own. They guide you through a specific set of questions that will allow them to know exactly what cartridge they used in the development of your faucet, sending you the correct one to keep the faucet functioning properly. If DoD could adopt a similar approach for items such as screws, sensor connections, tires, or windshields just as examples the design and development times can be reduced significantly.

Another commercial example is, all TV sets and mobile phones share some core set of capabilities, yet each model may have unique features. The PLA approach focuses on developing application families, rather than individual applications. From an economic perspective, the PLA investment pays off after as few as 4 to 6 systems, but the savings accrued in the end are more than worth the initial investment. Not surprisingly, companies such as Nokia, Motorola, and HP favor this approach. Unlike in these systems, DoD must consider more than just cost, they must also consider the effects on the warfighter. To that end, PLA are key enablers for capability on demand (CoD) as discussed in the next section.

The benefits of PLA for PBE are the following:

- **Reduced time to deployment**: Cummins, Inc. reports that systems that used to take a year to complete now can be turned out in about a week [9]

[9] Clements, P. and L. Northrop. *Software Product Lines: Practices and Patterns*. Addison Wesley, 2003.

- **Reduced cost**: For example, products in the National Reconnaissance Office's (NRO) Central Channel Toolkit product line cost approximately 10% of what they otherwise would have [10]
- **Increased productivity**: Cummins estimates that they are turning out 14x number of products than before, while using two-thirds the software resources[11]
- **Superior quality**: Each system is the beneficiary of defect elimination in its predecessors; higher developer and customer confidence; the more complex the system, the greater the benefit of having pre-solved performance, security, and availability problems
- **Simplified training**: Users conversant with working with one member of product line can competently work with others
- **Reduced logistics tail:** Fungibility of components reduces the number of spares required at the system of systems level
- **Increased competition:** Product lines present an inherently horizontal market, whereby industries can flourish across application pillars. Reduced barriers to entry allow more vendors to compete
- **Better leverage of human capital:** Platform savings are to a large extent due to design reuse. This allows human capital to focus further up the value chain. This is a significant benefit as the U.S. seeks to retain competitive militarily and economically
- **Agility and flexibility:** As a result of human capital advantage more focus can and will be provided at higher levels, adding flexibility and agility.

Cost Savings [12, 13, 14,15]	• Amortizes cost of core assets across all products that use them • Demonstrated repeatable per-product cost savings of 50% to 67% to 90% • One source of cost savings is higher developer productivity – shown to increase by 400% to 2100%
Time-to-Delivery[16]	• Shown to reduce time-to-delivery 50% to 90%
Duplicate Work Elimination	• Exploits commonality of systems and applies common, reusable components or features at a standard price
Superior Quality[17] **and Increased Predictability, Modeling Ability**	• Errors identified and corrected in one system are automatically eliminated from systems from the same product line • Defects have been shown to drop by 50% to 96%

Table 2: PLA Advantages

[10]Clements, P., S. Cohen, P. Donohoe, L. Northrop. "Control Channel Toolkit: A Software Product Line Case Study." *Technical Report CMU/SEI-2001-TR-030*. October 2001.

[11]McGreger, J. and P. Clements. "Better, Faster, Cheaper – Pick Any Three." MIT *Sloan Management Review.* submitted.

[12]Clements, P. and J. Bergey. "The U.S. Army's Common Avionics Architecture System (CAAS) Product Line: A Case Study." *Technical Report CMU/SEI-2005-TR-019.* September 2005.

[13]Cohen, S., E. Dunn, and A. Soule. "Successful Product Line Development and Sustainment: A DoD Case Study." *Technical Report CMU/SEI-2002-TN-018*. September 2002.

[14]"Catalog of Software Product Lines." *Software Engineering Institute, Carnegie Mellon*. 2010. http://www.sei.cmu.edu/productlines/ casestudies/catalog/

[15]Toft, P., C. Coleman, and J. Ohta. *A Cooperative Model for Cross-Divisional Product Development for a Software Product Line*. Kluwer Academic Publishers, 2000.

[16]Jensen, P. "Experiences with Product Line Development of Multi-Discipline Analysis Software at Overwatch Textron Systems." IEEE Computer Society Proceedings, SLPC 2007, Kyoto. September 2007.

[17]Pronk, B. "Medical Product Line Architectures." *Software Architecture TC2 First Working IFIP Conference on Software Architecture (WICSA1)*. (1999): 357-67.

A product line approach becomes a preferred approach when the intent is to build a family of systems. The key metrics by which this approach can be compared to others is in terms of cost, time to delivery, elimination of duplicate work, and quality (Table 2).

PLAs are open architectures, strictly speaking; they have "*published, accepted interfaces to components that can be provided by different vendors*." Whether PLAs, are open in a business sense (i.e., components for core assets come from different vendors) is a matter of business policy. For example, Nokia's product line for mobile phones is open outside Nokia, allowing different companies to use Nokia's core asset base to build their own phone products. Similarly, Hewlett Packard's product line for computer peripheral devices is open across widely disparate organizations within HP.

Above all, PLAs are responsive to DDR&E imperatives: a) accelerate delivery of technical capabilities to win the current fight; b) prepare for an uncertain future; c) reduce the cost, acquisition time, and risk of major defense acquisition programs.

There is also evidence in the Department to back up the projected impact, if adapted in a broader sense. DoD organizations that have adopted the product line approach include: Navy's Program Executive Office (PEO) Integrated Warfare System; NRO; Naval Undersea Warfare Center (NUWC), Army's Technical Applications Program Office (TAPO); Army's Live Training Transformation effort; Navy's PEO for Submarine Warfare Federated Tactical System family of systems. One particular DoD project, OneSAF PLA, bears some elaboration.

The OneSAF PLA provides tangible evidence in the Department to back up the projected impact of PLAs. OneSAF is the U.S. Army's next generation entity level simulation. As part of the acquisition and development of OneSAF, the U.S. used a task order acquisition plan. Under this plan, the Department developed an initial PLA Framework that was used to inform and guide the respective bidders for OneSAF Architecture and Integration (A&I) contract that was let in 2001. The successful A&I contractor is now responsible for the evolution and further development of the architecture.

C. Pilots and Research Efforts

The investment opportunity is in extending Product Lines from purely informational[18] to hybrid systems, i.e., systems spanning informational and physical systems and assets. Examples of physical assets are automated collection assets (e.g., sensors) and weapon systems. In this regard perhaps the best PLA for physical systems is space systems (satellites and launch vehicles). Indeed terms like booster, bus, launch vehicle, payload, immediately conjure the notion of product lines. The maturity of PLA in space is in no doubt due to the very high cost and risk of deploying assets in space. It is ironic that the two extremes of system costs (space on one side and PDAs on the other) have evolved PLA, while the vast middle ground remains untapped.

Electronic Warfare (EW) Systems: Rapid spirals of EW system upgrades make this a good domain for both MBE and PBE. Focus is on virtual design and modeling, with particular emphasis on electromagnetic compatibility with the battlefield system of systems, open architectures and rapid manufacturing services and trusted supply chains. **Research Partner:** Office of Naval Research (ONR) and PM JCREW systems engineering for future Naval Fleets.

[18] Burton, Mark. "Platform Based Design at the Electronic System Level." *Springer*. 2006.

Ground Vehicle: TARDEC also lends itself to PBE as an excellent pilot program, just as it did for MBE. As new requirements are identified, movement towards reuse and movement toward as streamlined PLA will benefit both PBE and MBE philosophies. **Pilot owner:** Army though TARDEC

ISR Systems: As mentioned several times within this report, satellite systems are excellent examples of developing PLAs for deployable ISR systems. Currently the Defense Advanced Research Projects Agency (DARPA) has a program, System F6, within the Tactical Technology Office (TTO) that tries to address the idea of a PLA in a unique way. Using the lessons learned and knowledge gained from this program, research can continue within this field but applied to various ISR spaces. **Research Partner:** DARPA and Service Laboratories

V. Capability on Demand

A. Definition

We define Capability on Demand (CoD) as designing systems or services that support adaptation to changing needs in the user environment. While there are many overlapping characteristics between CoD and PBE, there are some that are specific to CoD. These characteristics play into the fact that CoD enables systems to adapt post-deployment, while the adaptability within PBE is pre-deployment. These characteristics are as follows:

- **On-demand adaptability** is both passive and user-controlled
    - These systems maximize the plug and play features of systems. For instance, if an imaging sensor on a HMMWV is no longer required because of changing mission needs that requires a different sensor. A simple swapping of the sensor is possible in some cases. Ideally this type of capability will be expanded for a universal adoption.
- **Self-adaptive systems** include embedded sensors and embedded computing to assess changing state and allowing altered performance
    - Examples of some self-adaptive systems include cloud computing[19] (which adapt virtualization to user loads and computational demographics), and system oriented architectures[20] (which use software agents to adapt data formats to the situation at hand). We have little in the way of self adaptive systems presently outside of strict IT or cyber.
- **Field-adaptive systems** include user-selected reconfigurable capabilities and rapid human-computer adaptation.
    - Field adaptive systems are systems that can be modified during standard maintenance of a system. For instance, if a new type of HMMWV door is developed making them stronger, but lighter. These modifications can be made to the HMMWV when it is sent for its standard maintenance instead starting over from scratch with a brand new system. FPGA systems are another example of field adaptable systems, they adapt, but only when told when and how, with direct human intervention.

[19] Foley, John. "Gov 2.0: NASA Readies Mission-Oriented Cloud Computing." InformationWeek Government. 27 May 2010. June 25, 2010. http://www.informationweek.com/news/government/cloud-saas/showArticle.jhtml?articleID=225200398&queryText=cloud%20computing

[20] Reference model for service oriented architecture v1.0," November 2008. [Online]. Available: http://docs.oasis-open.org/soa-rm/v1.0/soa-rm.html

B. Findings

The technologies of embedded sensors, sensor networks, and embedded and autonomous computing are advancing at a remarkable rate. These technologies are arguably the most advanced technologies address within this report. However, that also makes them the least mature; therefore this solution space is very open ended. Self-adaptive systems should be possible from the integration of these technologies with user-environment knowledge. Adding virtual environments and massive knowledge-database management technologies should allow the design of user-selected reconfigurable systems. Finally, adding the scientific understanding from human-systems integration and augmented-cognition research should allow the design of field-adaptive (learning) systems. We analyzed these characteristics across the same industries as within the PBE section of the report, Figure 10. This again highlights several areas of improvement within this field, particularly in the IT/Cyber security realm. At first glance, this area is very adaptable with little research required. However, when we break out the cyber area, we find that this is not the case. The lower section of Figure 10 shows this. For instance, health monitoring is an area within IT/Cyber Security that requires additional research.

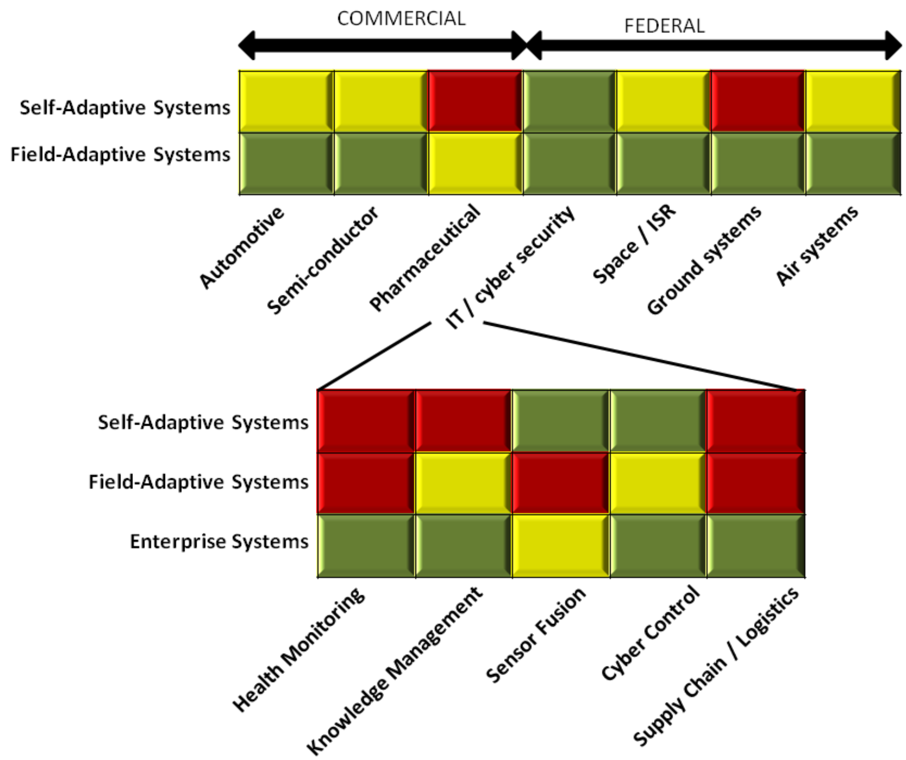

Figure 10: Capability on Demand Adaptability

1. Self-Adaptive Systems

The opportunity presented is the ability to generate an agile infrastructure that facilitates assessment of changing state, altered system behavior, and performance. The premise is that, in the commercial world, people have become accustomed to having CoD from cell phones, smart phones, net books, laptops, as well as desktop computers. If one needs a new application or service, one just looks on the Internet, finds it, and downloads it. This is now an expectation on the part of users—one poorly met in existing DoD environments.

To provide an advantage over a non-adaptive system, a complex adaptive system (CAS)[21] uses information that is relevant to local situations to *generate results at the tactical edge*. If the system is able to adapt on a physical- or software-level at the tactical edge it allows for a much faster and appropriate response time. This requires the inherent ability to Self-X (i.e., Self-Configuration, Self-Adaptability, Self-Optimization, and Self-Heal).

[21] Grisogono, Anne-Marie. *Action Group on Complexity Adaptive Systems for Defence*.

Furthermore, an adaptable system can morph itself to achieve the desired outcomes based on dynamic task definition in context. In order to achieve a Self-X system the current static system components have to be replaced or upgraded to components that can achieve the desired range of flexibility and adaptability. Self-adaptive systems should be possible from the integration of embedded sensors and autonomous computing with user-environment knowledge.

2. Field-Adaptive Systems

The incidence of unanticipated challenges to DoD systems is increasing, as is the complexity of decision situations. Difficulties arise from committing to human decisions made with limited opportunities to evaluate numerous complex options. We have the opportunity, now, to leverage the relative advantage of humans to deal with ambiguity and the relative advantage of technology to enable speed of processing and information visualization. Thus, wherever possible, there is great benefit to be derived from having synergetic human-computer option formulation and analysis before committing to a decision.

Leading indicators that can be subjected to combinations of autonomous analysis and inference, human-collaborative option generation, and synergetic human-computer option analysis precede many unanticipated challenges and opportunities. The idea here is to bring together the strengths of adaptive systems (for aggregation, recommender systems, and visualization) and emerging capabilities on the human side (such as crowd sourcing, virtual collaboration technology, social networking, and virtual exercise technology). As a result, combined human-computer intelligent systems will present the user with a set of options linked to needed and available resources to achieve a desired result in a specified environmental context.

Ongoing research has identified that field-adaptive systems require an adaptability reserve that needs to be engineered into each system to allow the capabilities to be discoverable, accessible, and useable (potentially among multiple other simultaneous users) in ways that cannot be preplanned. Reconfigurable/adaptable capabilities and services concerns approaches for developing and packaging software and hardware as services that are readily available in various venues such as publish/subscribe, searchable repositories augmented with recommender capabilities. Technologies/development approaches that enable redefined designing include modular design, loose coupling, and interoperability of services and systems based upon standards. Composable capabilities and dynamically composable middleware evolution will broaden opportunities for redefined architectures. What is new is defining the construct explicitly as inclusive of a merged systems engineering, operational, and artificial intelligence set of perspectives. This holistic view differs from the point optimality that is generally the focus of individual system design, used today and may require new concepts of optimality and reliability in both complex and adaptive systems.

Game engineering, or game theory[22], creates opportunities for system development to design the rules by which teams interact to compose large scale and complex systems. Mechanisms can be crafted to implement the outcome based on the planners' criteria of cost-minimization, reliability, rapid development, performance, and other factors relevant to the problem space. Since the very nature of large, complex systems prohibits centralized development, mechanisms to guide the distributed interactions are the key to implementing the desired behaviors and defining metrics. Game engineering holds promise for designing the rules, institutions,

[22] Nash, John. *The Work of John Nash in Game Theory*. Nobel Seminar. 8 December 1994.

and protocols which autonomous agents communicate, act, and are rewarded in order to implement the desired outcomes. For example, the sub-theory of mechanism design allows a system architect to design the interaction rules, or mechanism, through which the distributed system operates. The architect can design the mechanism to create the capabilities and desired outcome through the distributed operation of the system.

Currently, reconfigurable/adaptable capabilities and services can be described as a craft, wherein emergent features or side effects plague current systems. Additionally, ad hoc tools are used with each engineer or engineering team using a different tool set based on local experience and practice. Today complex adaptive systems are not engineered, but rather coped with. Adding virtual environments and massive knowledge-database management technologies to the integration of embedded sensors, autonomous computing, and user-environment knowledge should allow the design of user-selected reconfigurable systems. Finally, adding the scientific understanding from human-systems integration and augmented-cognition research should allow the design of field-adaptive (learning) systems.

C. Pilots and Research Efforts

Mobilization of Social Networks for Force Protection: This builds on the success of DARPA's Network Challenge (Red Balloon) and the recent success of University of Washington's Foldit video game[23]. These two exemplars use social networking, through either crowdsourcing (Red Balloon) or massive multi-player games (Foldit). The CoD field-adaptive capabilities will be used to locate and report a staged force-protection incident. The social network of interest will include both U.S. military personnel and non-military personnel in the test area. **Pilot owner**: DDR&E's Rapid Reaction Technology Office

Information Collection and Fusion for Force Protection: Will use rapid human-computer adaptation to provide situational awareness and a common operational picture. **Pilot owners:** Central Command (CENTCOM) or Naval Air Systems Command (NAVAIR). A recent article in the C4ISR Journal described the challenges of multi-INT information collection and fusion at the Combined Air Operations Center in Qatar. NAVAIR has a major investment in their Information Fusion Center and may wish to host a CoD pilot. A critical component here would be recommender system type technology to guide cell users to others with similar tasks and interests, as well as indicate recommended intelligence sources for examination.

Reconfigurable/Adaptable UAV Capabilities for Non-traditional Missions: Will show the benefits of pre-defined UAV capabilities and services in unanticipated circumstances. A particular mission of interest may be DoD counterdrug operations. While somewhat higher risk and longer period of time, UAVs have the ability to provide capability on demand across a wide swath of missions and applications, to include dynamic resupply in denied areas and supply chains. **Pilot owner(s):** Southern Command (SOCOM), Transportation Command (TRANSCOM)

Embedded Sensors and Computing: Research areas include rapid reconfiguration of hardware and software, low-energy equipment, and small-footprint, readily transportable devices. The focus here would be on health and status monitoring to enable rapid assessment of system reconfiguration in the field. **Pilot Owner:** RDECOM

[23] Markoff, John. "In a Video Game, Tackling the Complexity of Protein Folding." *The New York Times.* 9 August 2010. http://www.nytimes.com/2010/08/10/science/10gamers.html?_r=1&scp=1&sq=protein%20folding&st=cse

VI. Trusted Systems Design

A. Definition

In the context of this study, we define trusted systems design (TSD) as the ability to design trustworthy system from components and subsystems of unknown or suspect trustworthiness. The ultimate objective of TSD is the development of complex systems that provide assured performance and freedom from system vulnerabilities, malicious tampering, and exploitation opportunities. Applications span the space of systems security engineering, software assurance, and hardware assurance. TSD is mandated by the Systems-2020 imperative for system able to adapt post fielding. We simply cannot discount global technology and remain agile, hence the need to build in assurance with technology of imperfect pedigree.

Increases in malicious tampering and exploitation opportunities in combination with opaque supply chains and global COTS utilization present a unique challenge to engineers seeking to develop trusted, complex systems. Therefore, to have systems that are trusted we must have the ability to understand the weaknesses within a system, system components, be able to recognize anomalous behaviors within a system, trace them to the responsible components, and finally, be able to engineer trustworthy complex systems consisting of at time untrustworthy constituent parts.

B. Findings

Through our research, we discovered that the traditional protect-detect-react (PDR) strategy for countering system intrusions and attacks is ineffective. To regain our dominance we need a new strategy that augments PDR with the ability of systems and networks to survive attacks. Moreover, attackers are becoming ever-more resourceful in understanding their intended targets. They are thoroughly familiar with common vulnerabilities and weaknesses in commodity, open source, and other commonly-used technologies. As a result, these attackers are becoming increasingly skilled, inventive, and fast in designing attacks to compromise those targets. These creative individuals and groups can now launch zero-day attacks. A zero-day attack is one in which the defender cannot possibly keep up with and counter new attack strategies. These types of attacks are increasingly the norm; this can be seen in Table 3 in Appendix IV. Because of this, survivability requires more than simple resilience. It requires the ability to engineer systems that are less transparent to the attacker. Among solution identified are self-mutation and deception. Incorporating opacity and certitude of non-authorized agents into system design will increase the time attackers need to plan and craft attacks, delaying their ability to launch those attacks. Ultimately this will render the majority of attacks ineffectual. Collectively, these capabilities should narrow the window of opportunity for attack success so greatly that the zero-day advantage shifts from attacker to defender.

Many of the technologies needed to implement system self-mutation and deception have been individually researched, in some cases prototyped, and in a few cases productized. Some technologies that are commercially available include current software, system redundancy, and diversity techniques used for fault tolerance. These include n-version programming, macro-diversity, and diversity combining. As for deception techniques, there are code obfuscation, binary code encryption, and autonomic software adaptation techniques – i.e. techniques used by authors of polymorphic and metamorphic viruses and worms – to name a few. Enough research has been done on some techniques that will allow for near-term deployment; however, there is still extensive research required in these fields to gain a full appreciation of the techniques.

When most developers think of TSD, they immediately think of hardware and software assurance. These areas are probably the most technologically advanced in the field of understanding trust; however, there still exists many gaps in developing and using trusted hardware and software systems. Some areas where continued research is under development are in the measurement of trustworthy in existing components and for re-engineering/re-factoring components of insufficient or unknown trustworthiness. To do this, we must first understand flexibility models for trust evidence generation and computation. Current research in hardware trustworthiness assurance methods has largely focused on integrated circuits (IC) and IC assemblies. In this area, both the U.S. government and industry are making significant progress in risk mitigation and risk avoidance techniques. Within the federal government, both DoD and the Department of Energy are contributing significantly to research. In industry, the focus is in the financial sector with payment and bank card industries, with specific focus on the ICs used in smart cards.

Another aspect of great concern and research is within the counterfeiting community. Under the current DoD operating model, many systems, such as the B-52, are used for much longer than originally anticipated. As a result, many components are now obsolete, and alternatives must be developed for continued use of the system. With new components under development, the risk for counterfeiting, tampering, and malicious logic introduction increases, reducing our effectiveness. Testing techniques for hardware quality are long-established, and are being combined into various testing regimes for counterfeit detection. There are at least two efforts to standardize the set of inspections, analyses, and tests that should be performed for this purpose; they are SAE AS5553 and IDEA-STD-1010A. While most of these techniques are tool-assisted, the range of tools used, and their degree of specialization varies widely.

To address the gaps identified above, capabilities need to be developed in three core areas:

- **Full system architecture** for orchestrating opacity to non-authorized users
    - This will minimize exposure to threats, effectiveness of threats, and the systems internal misbehaviors and anomalies.
- System engineering approach **embedding TSD throughout the system life cycle**
    - Enables the specification of trustworthiness, attaining, and assuring requirements. The verification that system architectures/models exhibit all specified trustworthiness properties, and the verification that the system continues to exhibit those properties through sequentially more detailed iterations of design and implementation, enabling accurate attribution of trust
- Software and hardware **trustworthiness assessment** tools and methodologies.
    - The ***software toolkit*** would include tools for software vulnerability, integrity, anomaly, and functional intentionality analysis and testing, capable of operating on source code, intermediate code representations (byte code, assembler), and binary code.
    - The ***hardware toolkit*** would include tools for integrity, authenticity, and malware testing. Each toolkit would be accompanied by a Trustworthiness Verification and Validation (V&V) methodology, consistent with relevant standards (e.g., AS5553 and IDEA-STD-1010A for hardware authenticity testing), but not limited to the tests envisioned by any existing standard.

C. Pilots and Research Efforts

IC Trustworthiness Assessment Toolkit and Methodology: This pilot represents a proof-of-concept for an initial implementation of a toolset and methodology for IC trustworthiness assurance testing and inspection. The first step in this pilot is to assemble a toolkit and definition of an IC trustworthiness assessment methodology directing the combinations of tests to be performed to verify various trustworthiness properties of semiconductor devices (ICs, ASICs, FPGAs, SoCs, etc.). The methodology will draw from best elements of existing standard and widely-used Hardware QA and anti-counterfeit inspection methodologies. Second, a proof-of-concept use of the methodology and toolkit would be undertaken by pilot organizations which would document their observations and impressions of the methodology. They would measure the effectiveness of the toolkit to accomplish the methodology's trustworthiness assessment objectives as well as perceived deficiencies. Identifying other testing techniques and tools that could be added to the methodology and toolkit, either as is or with suggested adaptations. **Research Partner:** Air Force Research Laboratory (AFRL) with cooperation from the Defense Micro Electronics Activity (DMEA)

Cyber Auto-defense Prototype: This pilot will identify the most promising artificial intelligence-based autonomic technologies that could be used to prototype a working cyber auto-defense system. The resulting prototype would feature the ability to perform a wide range of activities in response to sensed anomalies and intrusion/exploitation-related events, including self adaptation in multiple ways and deceptive actions. The prototype would represent a proof-of-concept for gauging the viability, effectiveness, and maturity. **Research Partner:** DARPA’s Strategic Technology Office (STO)

VII. Next Steps

A. Integrated Roadmap

In the previous sections, we discussed several areas where research will help push forward the ideas identified through our research and interview. We also discussed several groups that may be amenable to working with DDR&E as a pilot exercise. Shown in Figure 11 is a roadmap of many of the ideas outlined previously in this report. These pilots are broken out into the specific Services, Army, Air Force, and Navy. There are some, such as the ISR Pilot and the Cyber Auto-defense Prototype that span all three services as well as the COCOMS so are not explicitly listed under a Service. Each of these pilots have been designed to complete execution prior to CY20 as noted along the x-axis.

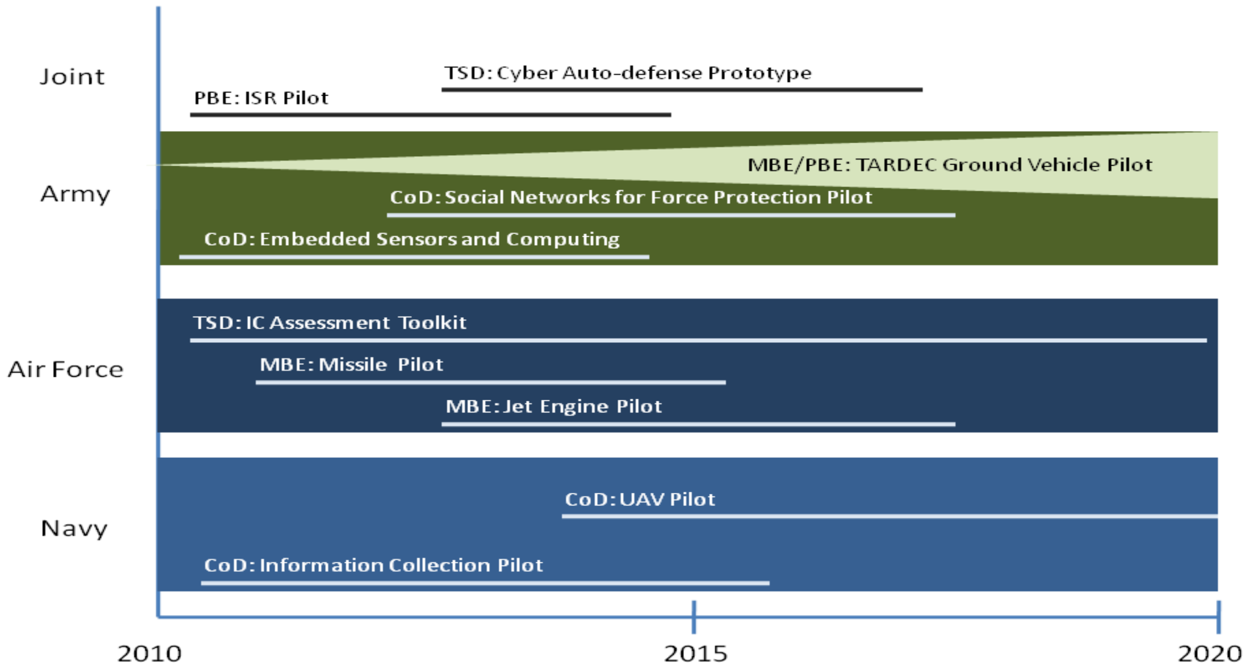

Figure 11: Integrated Pilot and Research Effort Timeline

B. Engagement Strategy

The ideas and recommendations brought forward in this report, either through research or industry interviews are cannot succeed unless we engage the Services, industry, the COCOMS, and others impacted by the research or its results. To this end, DDR&E leadership should closely examine the recommendations and ideas herein and collectively converge on an objective outcome of the Systems-2020 initiative. This clear concise object will prove the basis for a successful engagement strategy.

Once DDR&E Leadership identifies a concise objective for a full Systems-2020 program. We recommend that a team work closely with the Services to engage them in the pilots identified in the previous section, Integrated Roadmap. This team will ideally be a core group of DDR&E staff and representatives from each of the services. This team will reach out to the most appropriate pilot owners to engage in talks and planning for the integration into current programs underway with the pilot owners. For instance, for the CoD: UAV Pilot, the team will engage NAVAIR, working with them and SOCOM to identify an active project that is appropriate for Systems-2020. Once identified, the DDR&E team will work with the program manager of the project to identify shared funding opportunities, pilot specific objectives, and a timeframe for completion. This will in turn, allow for DDR&E to reach out to specific software tool developers and work with them to help form a new business model with the Department. This new model will encourage open source software tools, allowing for added collaboration and interoperability, as discussed in depth in the MBE section of this report.

Finally, in an effort to assist in the outreach to specific organizations like IEEE, AIAA, to name a few, we have listed in the table below upcoming conferences that could be excellent speaking engagements for informing the appropriate communities of the Systems-2020 initiative and its goals.

Conference	Dates	Location	Conference Website or POC
NATO Military Sensing Symposium	16-18 May 2011	Friedrichshafen, Germany	MinR Norbert Weber Germany Ministry of Defence norberyweber@bmvg.bund.de Dr. A Fenner Milton U.S. Army CERDEC NVESD Fenner.milton@us.army.mil
Conference on Systems Engineering Research	April 2011	Los Angeles, CA	www.incose-la.org/cser2011/
2011 IEEE International Systems Conference	3 – 6 April 2011	Montreal, CA	www.ieee.org
Dinner Meeting with INCOSE	TBD	Washington, DC	http://www.incosewma.org/
Military Engineering 2011	25-27 January 2011	Brussells, Belgium	www.epicos.com
3rd Annual International Conference on Model-Based Engineering	27-28 September 2010	Fairfax, VA	http://www.incosewma.org/
13th Annual Systems Engineering Conference	25-28 October 2010	San Diego, CA	http://www.ndia.org/meetings/1870/Pages/default.aspx

VIII. Appendix I: Survey Data Findings

State of Art: MBE	
3D Printing	
Provider	Stratsys, MakerBot, Objet, and others.
Description	3D printers construct three-dimensional objects one layer at a time directly from CAD drawings. Application to most physical systems.
Technical Challenge	Slow, limited materials
Non-Technical Challenge	High price of 3d units
Benefit	Ability to rapidly prototype objects or creates unique objects inexpensively.
NetCOS (Network-Centric Operation Simulation)	
Provider	EADS Defense & Science
Description	NetCOS, which is the multinational federating simulation environment for EADS network-centric solutions is a tool used within the System Design Centre (SDC) that is able to reproduce a realistic virtual battlefield encompassing the entire "sensor-to-shooter" chain, including the command, control and information networks.
Technical Challenge	Not an open source solution making interoperability challenging
Non-Technical Challenge	Lacking business model to make available for prime integrators
Benefit	The ability to simulate a realistic virtual battlefield assists in the design of network-enabled capabilities and large systems.
Radar Open Systems Architecture (ROSA)	
Provider	MIT Lincoln Laboratory
Description	ROSA decomposes traditionally tightly integrated radar into functional building blocks each with a well defined open source interface. Each of the blocks can be developed using COTS products and then assembled into fully functioning radar.
Technical Challenge	Maintain performance with COTS parts
Non-Technical Challenge	Needs buy in from the rest of industry to be effective
Benefit	horizontal industry for radar systems

State of Practice: MBE	
Aras Suite	
Provider	Aras
Description	Aras is a free Open Source PLM solution with fee-based subscriber support. It offers tools for program management, product engineering, quality planning, product data management, configuration and change management, restriction on hazardous substances, advanced product quality planning and lean manufacturing, among other modules.
Technical Challenge	Interoperability
Non-Technical Challenge	This tool is open source, which many agencies are not comfortable with as of yet.

Benefit	Open source, Microsoft .NET based, low cost alternative to the big names in PLM
BRL-CAD	
Provider	Open Source (www.brl.org)
Description	Cross-platform solid modeling system
Technical Challenge	Mature Technology
Non-Technical Challenge	Adoption by defense contractors
Benefit	Primary CAD system for vulnerability and lethality analysis of US weapons systems.
Cadence	
Provider	Cadence Inc
Description	Cadence's product offerings are targeted at various types of design and verification tasks which include tools for designing full-custom integrated circuits, creation of digital integrated circuits, simulation, and functional verification of RTL including Verilog, VHDL, and System C based models, Verification IP (VIP).
Technical Challenge	Mature Technology
Non-Technical Challenge	Specific to micro-electronics IC
Benefit	As of 2007 had 21% of the EDA market share according to AboutPLM.com.
CATIA, DELMIA, SIMULA, ENOVIA	
Provider	Dassault Systems
Description	PLM application software supporting industrial processes and providing a 3D vision of the product lifecycle. CATIA designs virtual products, DELMIA is for virtual production, SIMULA is for virtual testing and simulation, and ENOVIA is for managing the global collaborative lifecycle.
Technical Challenge	Ease of interaction
Non-Technical Challenge	Widespread acceptance
Benefit	Boosts innovation, ups quality and cost control. No need to build and test physical prototypes – virtual production will allow users to save resources and improve product quality simultaneously. Dassault is a market leader, and held 7% of the PLM market share in 2008. CATIA has been used by General Dynamics and Northrop Grumman to design submarines and super carriers for the US Navy. CATIA is used extensively in automotive manufacturing, and was used in Boeing's dreamliner.
Cobalt	
Provider	Ashlar
Description	Parametric 2 and 3D design software with a sophisticated non-linear user interface and extensive library of features.
Technical Challenge	Needs to be compatible with other industry applications
Non-Technical Challenge	All these tools require widespread acceptance
Benefit	Combines direct modeling and parametric strategies to create and edit objects, thus incorporating the ease of the direct approach with the rigor of the history-based approach. Easy to use, with a quick learning curve.

CORE	
Provider	Vitech
description	CORE is an integrated, model-based system engineering software tool which incorporates the key components of building a system: people, processes, data, and documentation.
Technical Challenge	Introducing physical models
Non-Technical Challenge	Widespread acceptance
Benefit	Integrate all aspects of design, and sustainability
DIRSIG	
Provider	RIT's Digital Imaging & Remote Sensing Lab (www.dirsig.org)
description	Physics-based synthetic image-generation model
Technical Challenge	Mature Technology
Benefit	Primary model for multispectral and hyperspectral, airborne or satellite imaging systems.
Modelica	
Provider	Modelica Association
Description	An object-oriented, declarative, multi-domain, equation based modeling language for component-oriented modeling of complex systems. Modelica is non-proprietary.
Technical Challenge	For system design the challenge is interoperable component descriptions
Non-Technical Challenge	Adoption by defense contractors
Benefit	Standard simulation language. The Modelica library contains a large set of available models including 920 model components and 620 functions. Commercial front-ends include SimulationX, MapleSim, MathModelica, Scicos, and CATIA.
Rational	
Provider	IBM
Description	Rational software helps in the development and manufacturing of products and in the integration of systems. Mainly for software design.
Technical Challenge	Mature Technology
Non-Technical Challenge	Applies mostly to software development
Benefit	Rational tools allow for the definition and management of requirements. Supports integrated collaboration by providing a central hub for cross-team communication, lifecycle traceability, rapid response to changing conditions, and version control.
Simulink and Real Time Workshop CONCEPT	
Provider	Mathworks (with several open source variants, Octave, Scilab)
Description	Simulink® is an environment for multi-domain simulation and MBE for dynamic and embedded systems.
Technical Challenge	Interoperability
Benefit	De-facto standard in industrial MBE
Synopsys	
Provider	Synopsys

Description	Synopsys is a world leader in electronic design automation (EDA), supplying the global electronics market with the software, IP, and services used in semiconductor design, and manufacturing. Synopsys' comprehensive, integrated portfolio of implementation, verification, IP, manufacturing and FPGA solutions helps address the key challenges designers and manufacturers face today, such as power and yield management, system-to-silicon verification and time-to-results.
Technical Challenge	Mature Technology
Non-Technical Challenge	Specific to the micro-electronic IC industry
Benefit	As of 2007 had 28% of the EDA market share according to AboutPLM.com.

State of Art: PBE	
Advanced Research & Technology for Embedded Intelligence and Systems	
Provider	European Consortium
Description	ARTEMIS aims to tackle the research and structural challenges faced by European industry by defining and implementing a coherent Research Agenda for Embedded Computing Systems.
Benefit	Robust focus on interoperability
Agent-based Hierarchies	
Provider	U Michigan: John Holland
Description	Founder of emergence theory, SW agents, genetic algorithms. Has developed a theoretical framework for modeling any complex adaptive system
Benefit	Allows for creation of multi-scale hierarchies using simple rule sets
Center for Hybrid and Embedded SW Systems	
Provider	University of California Berkeley
Description	Through their tools they are bridging the gap between computer science and systems science by developing the foundations of a modern systems science that is simultaneously computational and physical
Benefit	If successful adopts software engineering discipline to physical systems
Lean Advancement Initiative	
Provider	MIT
Description	The Lean Advancement Initiative (LAI) at MIT, together with its Educational Network (EdNet), offers organizational members from industry, government, and academia the newest and best thinking, products, and tools related to lean enterprise architecting and transformation.
Benefit	Possible community platform for defense engagement with tool vendors
Metropolois	
Provider	Center for Electrical Systems Design, UC Berkeley
Description	Metropolis consists of an infrastructure, a tool set, and design methodologies for various application domains. The infrastructure provides a mechanism such that heterogeneous components of a system can be represented uniformly and tools for formal methods can be applied naturally.

Benefit	Robust attempt at cross domain model integration
System Organization as a diagnostic tool	
Provider	Dr. Joel Moses, MIT
Description	The use of Organizational features (functionality invariant) as a means of assessing system agility: widely cited as a thought leader being application of standards and interface engineering adaptation.
Benefit	Provides a framework for assessing agility of complex systems

State of Practice: PBE	
PRO-Engineer	
Description	Pro/ENGINEER is a parametric, integrated 3D modeling tool geared to provide PLM solutions. Offers solid modeling, assembly modeling and drafting, finite element analysis, and NC and tooling analysis functionalities.
Technical Challenge	Compatibility with other tools in the market
Non-Technical Challenge	All these tools require widespread acceptance
Benefit	It was the first tool of its kind on the market. Allows users to edit designs dynamically through streamlined, automated task commands. Products can be developed from concept to manufacturing with one tool.
Rational	
Provider	IBM
Description	Rational software helps in the development and manufacturing of products and in the integration of systems. Mainly for software design.
Benefit	Rational tools allow for the definition and management of requirements, which helps reduce rework and promote efficiency. Supports integrated collaboration by providing a central hub for cross-team communication, lifecycle traceability, rapid response to changing conditions, and version control.
Rhinoceros	
Provider	Robert McNeel and Associates
Description	A stand-alone, NURBS based 3D object design, modeling, and editing tool.
Benefit	Lower price point makes it especially useful for early in the design process to generate, explore, and refine shapes. Boasts multi-disciplinary applications and a short learning-curve.
Siemens PLM	
Provider	Siemens
Description	Siemens Product Lifecycle Management Software Products is comprised of the widely used Teamcenter PLM framework, NX, which offers the industry's broadest suite of integrated, fully associative CAD/CAM/CAE applications and Tecnomatix, is a comprehensive portfolio of digital manufacturing solutions, as well as mid-market, lower cost versions of the software.

Benefit	Teamcenter is the most widely used PLM software. NX is also widely used. In a fragmented market Siemens has 6% of market share, as of 2008.

State of the Art: CoD	
The Agility Imperative	
Provider	David Alberts, Dir. Research OASD/NII www.dodccrp.org/html4books_main.html
Description	The Information Age has transitioned into the Age of Interactions. DoD is operating in a complex, dynamic environment and the only response is agility. Agility has both passive and active components.
Benefit	Sets the stage very well for passive and active CoD approaches.
Institute of Creative Technology	
Provider	Army and USC
Description	Apply virtual-reality, artificial intelligence and game technology to learning and training.
Benefit	Faster and better training of military personnel.
Pilot Associate	
Provider	DARPA
Description	Rapid human-computer adaptation
Benefit	If successful adopts software engineering discipline to physical systems
Project Oxygen	
Provider	MIT
Description	Pervasive human-centered computing
Benefit	Demonstration today of the benefits of adaptive embedded devices, handheld devices, and networked communications.
Human Systems Integration	
Provider	Brookhaven National Laboratory
Description	Developing intelligent operator aids for complex systems
Benefit	Standardized human-factors evaluation framework and acceptance criteria.
Embedded Systems Engineering	
Provider	Cihan Dagli (Missouri) and Mark Anderson (Boeing)
Description	Series of papers on systems engineering management
Benefit	Systems architecting heuristics based on B-1B bomber case studies.
Systems Engineering Advancement Research Initiative (SEAri)	
Provider	MIT
Description	Consortium-sponsored research on complex socio-technical systems
Benefit	Development of better theories, methods and effective systems engineering practices.

State of Practice: CoD	
Adaptive Embedded Sensors for Dual Use	
Description	Technical paper by Shu Chen and Wade Trappe (Rutgers) and Yingying Chen (Stevens) on an experiment to adapt a wireless sensing network for position verification
Benefit	Innovative field-adaptive service
Recommender Systems	
Provider	Amazon, Strands, eBay, Digg, Google, StumbleUpon
Description	Each company uses different proprietary algorithms for offering quality recommendations to their customers
Benefit	High-stake commercial competition will continue to drive the performance of recommender systems.
Embedded Sensors and Computing	
Provider	CL_2M Consortium
Description	European consortium for closed-loop, life-cycle management technology
Benefit	Added RFID and sensor characterization data to current technology offering
Mobile Robotics	
Provider	QinetiQ
Description	TALON family of robotics
Benefit	Providing military services since 2000
Augmented Cognition	
Provider	Honeywell and Oregon Health & Science University
Description	Real-time cognitive assessment of fatigue and stress
Benefit	Better situational awareness and overall mission effectiveness.

State of the Art: TSD	
Adaptive and Trusted Ambient Ecologies (ATRACO)	
Provider	Consortium led by Ulm University
Description	Advance the realization of trusted ambient ecologies for context-aware appliances, devices, artifacts, models, services, software components, etc. using internal trust models and fuzzy decision making mechanisms to adapt their operation to changing contexts. (www.uni-ulm.de/in/atraco)
Technical Challenges	Dependence on context-awareness of elements to benefit from trust limits adaptability/ extensibility (via middleware or wrappers?) to legacy components/ systems.
Benefit	Would increase trust-worthiness of ubiquitous computing; value would be even greater if approach adaptable to non-context-aware elements.

Autonomic Computing	
Provider	IBM Research Consortium
Description	Enable systems that manage themselves even as new components are integrated, so that computer systems regulate themselves much in the same way the autonomic nervous system regulates and protects the human body. www.research.ibm.com/autonomic/
Non-Technical Challenges	Even with 10+ years of research by IBM, no autonomic computing products have been released.
Benefit	Could finally demonstrate practicality of autonomic computing
Autonomic Network Defense	
Provider	Avirtec, Univ. of Arizona (Salim Hariri), EDAptive Computing
Description	Comprises: Engines for (1) automatic detection of abnormal behavior (demonstrated 99% accuracy), prevention of attack propagation, initiation of recovery; (2) automated resource deployment and configuration; (3) automated detection of/recovery from software and hardware faults; (4) automated resource allocation and scheduling; (5) Autonomia (Autonomic Control and Management Environment) toolset for system administrator specification of autonomic control and management schemes/policies. avirtec.com/index.php?option=com_content&task=view&id=22&Itemid=51
Non-Technical Challenges	Even with participation of 2 commercial firms, autonomic computing remains research-mature after more than 10 years.
Benefit	Could finally demonstrate practicality of autonomic computing
Clean-Slate Design of Resilient, Adaptive, Secure Hosts (CRASH)	
Provider	DARPA TCTO
Description	Design of new computer systems that are highly resistant to cyber-attack, can adapt after a successful attack and continue rendering useful services, learn from previous attacks how to guard against and cope with future attacks, and repair themselves after attacks have succeeded. (www.darpa.mil/tcto/solicitations/BAA-10-70.html)
Non-Technical Challenges	How effective the outcomes of this research will be will depend on how widely DARPA allows research results to be disseminated beyond use in military technology.
Benefit	Potential to improve survivability of systems – value increased by making technology available outside military systems.
Complex Interdependency Modeling and Analysis	
Provider	Team for Research in Ubiquitous Secure Technology (TRUST)
Description	Integrated system and security modeling infrastructure of modeling, design, analysis, and operational techniques/tools to reduce vulnerability of complex adaptive networks to disruptive failure through model-based trusted system integration. www.truststc.org/systemsScience.htm

Technical Challenges	Not clear whether approach will be adaptable to systems other than adaptive networks.
Benefit	Limited if not adaptable to more than adaptive networks.
Comments	Complex Interdependency Modeling and Analysis
Component-ware for Autonomic Situation-aware Communications, and Dynamically Adaptable Services (CASCADAS)	
Provider	14-member consortium: http://acetoolkit.sourceforge.net/cascadas/partners.php
Description	Autonomic component-based framework designed to enable composition, execution, and deployment of flexible services capable of dynamically self-adapting to unpredictable, evolving environments and situations. acetoolkit.sourceforge.net/cascadas/
Non-Technical Challenges	Move of CASCADAS from EC Framework Programme to Open Source may be promising indication that actual implementations may be near.
Benefit	Could finally demonstrate practicality of autonomic computing
Danger Project	
Provider	Professor Uwe Aickelin, University of Nottingham (UK)
Description	Focuses on application of Danger Theory to creating artificial immune systems that are not limited in scalability by reliance on self/non-self discrimination theory. www.dangertheory.com/
Technical Challenges	Lack of widespread adoption of Danger Theory may render artificial immune system modeling more difficult, due to lack of real-world models on which to base.
Non-Technical Challenges	Danger Theory still highly controversial as model for human immune system behavior; shouldn't be an issue, unless project funding depends on accuracy of biologically-inspired models.
Benefit	Could finally demonstrate practicality of artificial immunology for improving system survivability
Designing for Value Robustness	
Provider	MIT
Description	Value robustness is the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs. An example of this is architectural principles and strategies for designing survivable systems. seari.mit.edu
Non-Technical Challenges	For Value Robustness to be effective for promoting trustworthiness, the value of trustworthiness must be quantified by system stakeholder – but few organizations know how to do this.
Benefit	Could finally provide a basis for true ROI under-standing/ business case for SW trustworthiness
Detection of malicious integrated circuit functions (hardware Trojans)	

Provider	Jim Plusquellic(Univ. of New Mexico) Ahmad-Reza Sadeghi, Ruhr-Universität Bochum; Dakshi Agrawal, Berk Sunar, Selcuk Baktir, and Deniz Karakoyunlu (Worcester Polytechnic Institute) Gedare Bloom, Bhagi Narahari, and Raul Simha (George Washington Univ.) Jie Li and John Lach (Univ. of Virginia) Mehrdad Majzoobi, Farinaz Koushanfar, and Hassan Salmani (Rice University) Michael S. Hsiao and Sumit Kumar Jha (Virginia Tech) Miodrag Potkonjak (UCLA) Pradeep K. Rohatgi (Univ. of Wisconsin, Milwaukee) Rajat Subhra Chakraborty, Francis G. Wolff, Somnath Paul, Christos A. Papachristou, and Swarup Bhunia (Case Western Reserve) Samuel T. King (University of Illinois at Urbana Champaign) Susmit Jha (Univ. of California-Berkeley) Xiaoxiao Wang and Mohammad Tehranipoor (Univ. of Connecticut-Storr) Yier Jin and Yiorgos Makris (Yale University)
Description	Integrated circuit (IC) testing techniques to discover indications of malicious logic using a variety of detection methods and test modalities.
Technical Challenges	Requires repurposing of tools (that are often expensive). No effort yet made to design special purpose tools. Limited efforts to combine test approaches for increased detection rate.
Non-Technical Challenges	The technologies involved are still quite new and untried outside research labs.
Benefit	Improved IC assessment ability beyond design conformance and authenticity
Extensible Architecture for Homeostasis in Electronic Systems	
Provider	Andy Tyrrell, University of York (UK)
Description	Architecture for engineering electronic systems that can predict, or be aware of, imminent threats when operating within highly dynamic environments, and alter their own physical and operational states and configurations to circumvent the effects of those threats. www.elec.york.ac.uk/research/intSys/bioInsp/ais.html and gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E005187/1
Technical Challenges	Still awaiting practical real world implementation of artificial immune system (which is basis for this research)
Benefit	Could finally demonstrate practicality of artificial immunology for improving system survivability
FXplorer and Function Extraction (FX) for Software Assurance	
Provider	Carnegie Mellon Univ. (CMU) Software Engineering Institute (SEI) STAR*Lab
Description	Automates calculation of software's functional behavior to the maximum extent possible, to provide precise information on the structure and function of malicious code.
Non-Technical Challenges	As with many CMU SEI projects, lots of documentation exists, but still awaiting tech transfer and tool availability.

Benefit	With commodification, could be "sea change" technology for software security assessment, filling gap vis detection of malicious logic
Genetic Message-Oriented Secure Middleware (GEMOM)	
Provider	EU FP7 research consortium
Description	Prototype secure end-to-end messaging platform that is self-organizing and self-healing, enabling instantaneous hot-swap or switchover to redundant modules by specialist, independent system actors such as watch-dogs, security/situation monitors, routers, and optimizers without information loss or compromise of higher level functionality. (www.gemom.eu/public/modules/mastop_publish/)
Technical Challenges	Still awaiting practical real world implementation of artificial immune system (which is basis for this research)
Benefit	Could finally demonstrate practicality of artificial immunology for improving system survivability
Helix self-regenerative architecture	
Provider	Univ. of Virginia Dependability Research Group
Description	Combined metamorphic defense mechanisms that present attackers with a continuously changing attack surface as attacks progress, an innate response mechanism that creates more aggressive system metamorphosis for containing effects of unavoided attacks and reconfiguring the system for rapid recovery/continued service, and adaptive response learning mechanism that ensures repairs enable the system to deflect the same/similar attacks in future. (dependability.cs.virginia.edu/info/Helix)
Non-Technical Challenges	As with many UVA Dependability Research projects, lots of documentation exists, but still awaiting tech transfer and tool availability.
Benefit	Significant advance towards self-protecting, survivable complex systems
Model-Based Integration of Secure Systems	
Provider	TRUST
Description	A trusted component integration platform will enable runtime middleware components to monitor and enforce adaptive resource management policies so that applications degrade gracefully under attack. (www.truststc.org/systemsScience.htm)
Technical Challenges	Need to assure that the middleware components are trustworthy.
Non-Technical Challenges	Adoption that is widespread enough, esp. among cloud/utility computing providers, to make a difference, esp. as increasing amount of ICT is outsourced to "as a service" models.
Benefit	If standardized and widely adopted by service providers, could have big positive impact.
Proof-carrying code	
Provider	George Necula, Univ. of California-Berkeley; Peter Lee, CMU

Description	Mechanism for establishing trust needed for safe execution of untrusted code by requiring the code to be delivered with a formal proof of its adherence to required properties/adherence to appropriate policies (e.g., safety, security, functionality policies). raw.cs.berkeley.edu/pcc.html & www.cs.cmu.edu/~fox/pcc.html
Technical Challenges	Assumption is that infra-structure exists to enable all software elements in system to detect, decipher, and act upon proofs.
Non-Technical Challenges	Practicality for COTS products not yet demonstrated. Only hope of widespread adoption is a standard (de jure or de facto) supported by major SW vendors (e.g., Microsoft). (Code signing for mobile code provides model for how widely PCC is likely to be adopted.)
Benefit	Significant potential improvement over code signing for trust-worthiness verification at run-time
Comments	Proof-carrying code
Scalable Trustworthy Network Computing (STNC)	
Provider	Jack Dongarra, Univ. of Tenessee Innovative Computing Lab
Description	Enable use of untrusted intermediaries and end-to-end protocols to implement a scalable network computing with adequate trustworthiness for a wide spectrum of applications. netlib.org/utk/people/JackDongarra/PAPERS/position-trustworthy.pdf
Non-Technical Challenges	Extremely ambitious attempt to solve the disconnect between non-scalability of most security applications and global scale of Internet.
Benefit	Significant advance towards adding trust-worthiness to systems on the Internet
Security Metrics and Policy Evaluation	
Provider	DePaul University (Ehab Al-Shaer)
Description	Comprehensive security metric framework that identifies and objectively quantifies the most significant security risk factors, including existing and future vulnerabilities (identified based on historical trends), security configuration immunity to attack occurrence and propagation, and traffic trends that characterize insider and outsider user behaviors. (www.mnlab.cs.depaul.edu/projects.php)
Technical Challenges	Presumes that sufficient metrics – and techniques for measurement – will exist to make the framework useful.
Benefit	Potential to make security/ trustworthiness more easily quantifiable, and thus demonstrable.
Security of Software for Distributed Applications (SEC SODA)	
Provider	Katholieke Universitiet Leuven DistriNet and COSIC research groups (Lieven Desmet)

Description	Techniques for adding trustworthiness to existing software components at deployment or run-time. These include: security-aware software architectures in which security properties can be accommodated and their effectiveness verified; programming models that provably guarantee absence of particular security problems; techniques for integration of specialized security measures into a security-unaware and untrusted software artifacts; technologies for trustworthy deployment of secure software, including self-protecting code, encrypted execution, and remote attestation. distrinet.cs.kuleuven.be/projects/secsoda/overview/index.html
Technical Challenges	Getting beyond limitations of "wrappers" and current refactoring/ reengineering approaches.
Benefit	Enables trust-worthiness improvements in legacy systems
Software component diversity	
Provider	Univ. of Virginia; Katholieke Universitiet Leuven
Description	Different functionally-identically but implemented distinct versions of software programs or components (developed from the same specification) are deployed to add robustness to component redundancy schemes, by ensuring that not all functionally-identical components harbor the same vulnerabilities or are susceptible to the same attacks/failures.
Technical Challenges	Practicality of diversity implementation is still under debate, as is the improvement in reliability of diversity vs. simple redundancy of homogeneous elements if the differences in diverse versions aren't great enough.
Non-Technical Challenges	As with many UVA Dependability Research projects, lots of documentation exists, unclear whether it will ever reach tech transfer and tool availability stage.
Benefit	Potential to make diversification of system components easier to achieve and manage, for improved survivability
Trust4All	
Provider	Information Technology for European Advancement (ITEA)
Description	Middleware architecture for embedded systems that require a defined level of trustworthiness/assurance; includes trust model, dynamic monitoring metrics, and methodology. Based on the Trust4All validation process, systems will be allowed to, or prevented from, executing applications or services of a given level of confidence. www.hitech-projects.com/euprojects/trust4all/
Technical Challenges	Not clear whether approach will be adaptable to non-embedded systems.
Benefit	Improved trust-worthiness of embedded systems; even more value if adaptable to non-embedded elements.
Trusted ILLIAC	
Provider	Univ. of Illinois-Urbana-Champaign Information Trust Institute
Description	Low-cost configurable trusted cluster computing platform for research into trusted utility computing/adaptive enterprise computing. www.iti.illinois.edu/content/trusted-illiac

Technical Challenges	Intended for use by researchers, so unclear whether robust or scalable enough (now or ever) for tech transfer to real-world use.
Non-Technical Challenges	Easily accessible open source implementation is needed to ensure Trusted ILLIAC serves its intended purpose.
Benefit	Only valuable if widely adopted by researchers, as intended, for producing better systems
Trustworthy Ambient Systems (TrAmS)	
Provider	Newcastle (UK) University
Description	Approaches for fault-tolerant, dependable engineering of ambient (mobile) systems absent design-time knowledge of system run-time structure. www.cs.ncl.ac.uk/research/current%20projects? pid=223
Technical Challenges	Not clear whether approach will be adaptable to non-ambient systems.
Benefit	Improved trust-worthiness of mobile systems; even more value if adaptable to non-mobile elements.

State of the Practice: TSD	
Analyses and tests to detect common software vulnerabilities and weaknesses	
Provider	Coverity, Fortify, Ounce, Klocwork, Open Web Application Security Project (OWASP), Mitre Corp., and OMG
Description	Methodologies, tools, & supporting technologies, for comprehensive software security analysis and testing, usually requiring source code. Assumption for most tools/techniques is that analyses/tests will be done pre-integration.
Technical Challenges	over-reliance signatures vs. more advanced techniques leads to unacceptable false positive/false negative rates, lack of effective techniques or tools for detecting malicious logic built into software, lack of methodology for correlating architecture/design analyses with code reviews, pre-integration tests, post-integration vulnerability scans, penetration tests, etc. to get full picture of what findings collectively say about software's trustworthiness
Non-Technical Challenges	excessive focus on "absence of vulnerabilities" as only indicator of trust-worthiness
Benefit	Potential for moderate trust-worthiness improvement only, due to test method, technology, tool limitations
Model-driven engineering (MDE) for trustworthy system development	
Provider	Motorola
Description	Areas of MDE are directly applicable to developing trustworthy computing systems: • Automatic generation of code eliminates coding-related errors and eases implementation of cross-cutting policies and capabilities • Increased developer productivity allows more time for security analyses/ tests
Technical Challenges	With exception of 2 OMG UML profiles, no explicit concern for trustworthiness, security properties, in MDE. Lack of supporting tools. Well-understood SW metrics don't apply to model evaluation (e.g., lines of code)

Non-Technical Challenges	Modeling is difficult. Lack of acceptance of MDE by many risk-averse PMs and developers who don't understand it, or don't trust the auto-generated code.
Benefit	Potential for elimination of coding-related faults/ vulnerabilities IF widely adopted.
Practical Measurement Framework for Software Assurance and Information Security	
Provider	DOD/DHS/NIST Software Assurance (SwA) Measurement Working Group (Nadya Bartol)
Description	Approach to use of qualitative & quantitative methods/techniques to assess assurance of software. buildsecurityin.us-cert.gov/swa/downloads/ SwA_Measurement.pdf
Technical Challenges	Deficiencies in what metrics/ measurements are possible at this point (see entry on Technical Metrics below) renders Framework of limited value in short term. Not sure Framework will be adaptable enough to remain useful when sufficient metrics and measurement techniques are available.
Benefit	Unclear given current immature state of trust-worthiness relevant metrics
Quality- or high-confidence software methods for developing secure software systems	
Provider	Lawrence Bernstein (Stevens Institute of Technology), Anthony Hall (Altran Praxis)
Description	Using development methods conceived for developing high-confidence software to produce secure software systems.
Technical Challenges	Effectiveness of formal methods has yet to be demonstrated for verifying trustworthiness based on security as a required property (due to difficulty modeling non-functional properties and impossibility of proving negatives). Formal methods, on which many such methods are based, are extremely labor intensive, and thus have proved practical only for small, special purpose programs.
Non-Technical Challenges	These methods do not explicitly address security.
Benefit	Better quality has limited impact on trust-worthiness or survivability. Compared to today's SW, any improvement is better than current status quo – but definitely not sufficient for high- or even medium-assurance
Secure System/Software Development Methodologies	
Provider	CMU SEI (James Over), OWASP (John Viega), Microsoft Corp. (Michael Howard, Steve Lipner)
Description	Articulate critical security/ trustworthiness and assurance concerns, principles, practices, artifacts, to be embedded throughout the SDLC.
Technical Challenges	All such methods require developers to have special security training and/or development team to include software security specialist(s).
Non-Technical Challenges	Aside from SDL (used by Microsoft), not clear how widely such methods are being adopted. Plus, they unavoidably add effort/cost to SDLC.
Benefit	Unable to gauge based on experience to date. Prolifera-tion of methods suggests none has hit on the right formula yet
Technical metrics for systems security measurement	
Provider	Robert Martin, Mitre Corp.; OWASP; Pete Herzog, ISECOM

Description	Metrics and measuring techniques for technical security measurement of components or systems.
Technical Challenges	No real consensus yet on what needs to be measured (correctness / robustness of security controls vs. indications of trustworthiness) and what the resulting measurements say about overall system trustworthiness. Wide variety of metrics for various contexts (business, technical, operational, etc.) but few if any techniques/tools for correlation and interpretation across all collected measurements.
Benefit	Current metrics of limited value for accurate trust-worthiness determi-nation.
UML Profile for Modeling Quality of Service and Fault Tolerance Characteristics and Mechanisms	
Provider	Object Management Group (OMB)
Description	Set of UML 2.0 extensions that represent QoS and Fault-Tolerance properties, integrated into QoS Modeling Framework and FT Modeling Framework.
Technical Challenges	QoS and fault-tolerance are trustworthiness properties, but not explictly oriented to security. OMB has yet to release UML profiles explicitly addressing security. Third-party UML security extensions (e.g., UMLSec) focus on security functionality, not trustworthiness.
Benefit	For those that use UML, could make modeling of trustworthy systems (trust based on reliability vs. security) somewhat easier.

IX. Appendix II: People Interviewed and Literature Surveyed

Name	Organization	Title
Alberto Sangiovanni-Vincentelli	University of California at Berkeley	Professor, Electrical Engineering and Computer Science
Allen Thompson	Booz Allen Hamilton	Principal
Anne-Marie Grisogono	Defence Science and Technology Organisation	Research Leader
Art Fritzson	Booz Allen Hamilton	Officer
Arthur Dougas	Booz Allen Hamilton	Principal
Azad Madni	USC	Professor and Director Systems Architecting and Engineering Program
Barry Boehm	USC	TRW Professor of Software Engineering Director of Research, Stevens-USC Systems Engineering Research Center Director Emeritus, USC-CSSE
Barry Ives	Lockheed Martin	Engineering Manager
Ben Riley	Office of the Secretary of Defense, Acquisition, Technology and Logistics	Director, Developmental Test and Evaluation
Bob Graybill	Nimbiss Services, Inc.	President, CEO
Brian Abbe	Booz Allen Hamilton	Principal
Brian Hibbeln	Undersecretary of Defense (Intelligence)	Director, Special Capabilities Office
Buck Adams	Booz Allen Hamilton	Principal
Caesar Mamplata	Booz Allen Hamilton	Associate
Carl McCants	DARPA	Program Manager
Charlie Hamilton	Booz Allen Hamilton	Principal
Charlie Zuhoski	Booz Allen Hamilton	Officer
Dan Kaufman	Defense Advanced Research Projects Agency	Director, Information Processing Techniques Office
Dave Honey	DDR&E	Director for Research
David Whelan	Boeing, Phantom Works	Vice President-General Manager and Deputy
Dave Young	Booz Allen Hamilton	Senior Associate
Dean Collins	Former Defense Advanced Research Projects Agency	Former Deputy Director, Microsystems Technology Office
Dell Lunceford	Gaia Patterns LLC	Modeling Simulation Vice President
Dick Johnson	Booz Allen Hamilton	Principal
Donny Holaschutz	Booz Allen Hamilton	Associate
Dov Zakheim	Booz Allen Hamilton	Officer
Ed Splitt	Booz Allen Hamilton	Senior Associate
Frank Sizemore	Booz Allen Hamilton	Associate
Greg Wenzel	Booz Allen Hamilton	Officer
Henry Obering	Booz Allen Hamilton	Officer
Jack Welsh	Booz Allen Hamilton	Officer
James Hvizd	EADS	Vice President, Transport / Mission Aircraft

James Thompson	Director, Defense Research and Engineering	Director, Major Program Support
Janos Sztipanovits	Vanderbilt University	Professor and Director of Institute for Software Integrated Systems
Janet Lyman	Booz Allen Hamilton	Officer
Jim Carlini	Carlini & Associates Inc	President
Jim Kee	Booz Allen Hamilton	Principal
John Doyle	California Institute of Technology	Professor, Control and Dynamical Systems, Electrical Engineering
John Eicke	U.S. Army Research Laboratory	STO Manager
John Erickson	U.S. Air Force Research Laboratory	Tech Advisor
John Goodenough	University of Texas, Austin	Professor, Mechanical Engineering
John Thomas	Booz Allen Hamilton	Officer
Joseph Koegh	Booz Allen Hamilton	Principal
Keith Catanzano	Booz Allan Hamilton	Senior Associate
Karen Goertzel	Booz Allen Hamilton	Lead Associate
Kevin Gooch	Booz Allen Hamilton	Principal
Larry Burns	General Motors	Former Vice President, Research & Development and Strategic Planning
Marie Francesca	The MITRE Corporation	Director, Corporate Engineering Operations
Mark Pflanz	Booz Allen Hamilton	Lead Associate
Mike Mcgrath	Anser Corp	Former DARPA PM, modeling
Naresh Shah	Kinsey Assoc.	Director, Defense and Intelligence Community Programs
Nicholas Torelli	DDR&E	Deputy Director, Systems Engineering / Mission Assurance
Pat Garrett	Booz Allen Hamilton	Senior Associate
Paul Eremenko	DARPA	Program Manager, Tactical Technology Office
Renee Stevens	The MITRE Corporation	Senior Principal Engineer
Richard Jaskot	Booz Allen Hamilton	Principal
Rick Morrison	Booz Allen Hamilton	Principal
Ron Kadish	Booz Allen Hamilton	Officer
Scott Wartenberg	Booz Allen Hamilton	Lead Associate
Scott Welles	Booz Allen Hamilton	Vice President
Sevario Fazzari	Booz Allen Hamilton	Lead Associate
Steve Soules	Booz Allen Hamilton	Vice President
Terry Wilson	U.S. Air Force Research Laboratory	SIP CTA LEAD
Thomas Fuhrman	Booz Allen Hamilton	Officer
Tom Jones	Booz Allen Hamilton	Senior Associate
Troy Peterson	Booz Allen Hamilton	Senior Associate

21st Century Strategic Technology Vectors	
Authors	Defense Science Board
Source	Defense Science Board 2006 Summer Study
Summary	The report highlights enhanced training and continuous education, automated language processing, close-in sensor systems and the soldier as a collector in a network, rapid extraction of the information hidden in massive amount of data and non-kinetic operations. It also points to the potential of models from the social and behavioral sciences to understand better how individuals, groups, societies, and nations are likely to act in response to changing circumstances.
Concept Engineering: Turning Stakeholder Needs into CONOPS for System Design	
Authors	SERC
Source	Report SERC-2010-Tr-007 May 31, 2010
Summary	Very detailed review of concept engineering, how it applies to system design. What an architecture built around it might look like, and some militarily relevent examples.
A Foundation for Interoperability in Next-Generation Product Development Systems	
Authors	Simon Szykman
Source	Foundation IPDS
Summary	The ability to have information used or generated during various product development activities to feed forward and backward into others by way of direct electronic interchange is in significant demand for the next wave of computer-aided engineering software tools to improve interoperability between software and to reduce the billions of dollars spent because of this poor interoperability .
A Network Diversion Vulnerability Problem	
Authors	Ariel Cintron-Arias
Source	Cornell University
Summary	A good discussion of graph partitioning algorithms relevant to system decomposition algorithms in general.
A New Look at Systems Engineer	
Authors	Robert Frosch
Source	Asst Secretary to the Navy/Pentagon
Summary	He makes the case for a deeper and more broadly trained leadership, as opposed to "process" for risk mitigation in Complex Adaptive Systems.
Abstraction Based Complexity Management	
Source	DARPA META Program, Appendix F
Summary	Discusses the complexity metric derived from the DARPA META program. The model is based on interconnects, and while primitive does provide some initial glimpses at what a complexity theoretic Complex Adaptive System model might look like.
Acquisition Strategies for Dealing with Uncertainty	
Authors	Renee Stevens
Source	6th Annual Acquisition Research Symposium of the Naval Postgraduate School

Summary	Based on a multi-year research program that investigated how uncertainty-based acquisition methods can be used to improve the odds of successful IT acquisitions. The paper presents new concepts for managing uncertainty as well as a three-step approach to their implementation. More than 20 acquisition program were studied and pilot programs were initiated to test the frameworks and strategies suggested in the research.
Action Group on Complexity Adaptive Systems for Defence	
Author	Anne-Marie Grisogono
Summary	The Action Group seeks to raise the level of capability in the participating nation's ability to deal with current and emerging intractable defense problems where complexity is the source of their difficulty. The study explores the implications of complexity theory, and in particular, the science of complex adaptive systems, for major defense challenges arising from complexity, and in developing those implications into practical applications, tools, techniques and approaches to improve defense effectiveness in the face of those challenges.
Adaptive Stance	
Author	Anne-Marie Grisogono
Summary	Military organizations interact with Complex Causal and Influence Networks all the time. The Adaptive Stance is a necessary complement to traditional Mission Command and involves making the whole chain of command, down to the individual soldier-as-sensor more flexible and adaptable.
An MDP-Based Recommender System	
Authors	Guy Shani
Source	Ben-Gurion University, Journal of Machine Learning, Vol 6, 2005
Summary	Most current systems use eigenvector analysis for recommender systems. This paper explores the use of Hidden Markov Models. This is still in its infancy, but appears to hold promise.
Avoiding Technology Surprise for Tomorrows Warfighter: A Symposium Report	
Authors	Committee for Symposium on Avoiding Technology Surprise for Tomorrows Warfighter, National Research Council
Source	http://www.nap.edu/catalog/12735.html
Summary	This report makes the case that we can and must do better do better at predicting surprise, using a combination of data mining and subject matter experts for technology scouting.
Building Executable Architectures of Net Enabled Operations Using State Machines to Simulate Concurrent Activities	
Authors	Ronald Funk
Source	Centre for Operational Research and Analysis Ontario, Canada
Summary	Investigates the possibility of using State-Machine models of processes that can be represented in the serial Task-Process-Exploit-Disseminate cycle or the concurrent Task-Post-Process-Use cycle. While there are limits to the State-Machine model, the author's preliminary work concludes that research should continue in this area.
Causal and Influence Networks in Complex Systems	
Authors	JSA (The Technical Cooperation Program)
Source	Action Group 14 Complex Adaptive Systems for Defense
Summary	AG14 progress report outlining preliminary approaches to determining how causation works in complex systems. Their investigations launched a multinational effort to continue research in this area now that the Action Group's mandate has expired.

Challenges and Solutions for Late and Post Silicon Design	
Authors	Jan M Rabaey
Source	University of California, Berkeley
Summary	Describes the decline in number of ASIC designs despite exponential market growth. Makes the case that we are in serious need of new design tools.
Comparing Genomes to Computer Operating Systems in Terms of the Topology and Evolution of Their Regulatory Control Networks	
Authors	Koon-Kiu Yan
Source	PNAS
Summary	The genome has often been called the operating system for living organisms. The key difference is the transcriptional regulatory network possesses a few global regulators at the top and many targets at the bottom. The key similarity is the emergence hierarchy because it is an effective way to transfer information and control processes.
Complex Adaptive Systems Engineering (CASE)	
Authors	Brian B White
Source	Mitre SEPO Collaboration
Summary	CASE is based on evolutionary processes that abound and thrive in nature and other complex environments (such as human language development), and is meant to be complimentary to conventional SE methods that sometimes fail in complex environments. Before being applied more broadly, CASE has been considered as a methodology suitable for complex environments since it acknowledges the human factor and encourages exerting influence rather than control. Contains a good summary of failed programs in DoD and a best practices checklist for managing complex systems.
Complex Adaptive Systems of Systems (CASoS) Engineering	
Authors	DHS Economic Roundtable
Source	Office of Infrastructure Protection, Department of Homeland Security
Summary	DHS study on the failure modes of Systems of Systems. Good list of references on Complex Adaptive Systems model for failure prediction. Presented as examples infectious disease and the global financial system.
Complexity Theory and Organization Science	
Authors	Philip Anderson
Source	Institute for Operations Research and the Management Sciences
Summary	Complex adaptive system models are a new way to simplify complex problems but organizational theory has not yet caught up with the new emerging tools to analyze their behavior. They are categorized by four key elements: agents with schemata, self-organizing networks sustained by importing energy, co-evolution to the edge of chaos, and system evolution based on recombination.
Critical Success Factors for Rapid, Innovative Solutions	
Authors	Jo Ann Lane
Source	Modeling Concepts Today's Software Proc, Intl Conf Germany 2010

Summary	An investigation of the traits of successful innovative organizations. Emphasizes the importance of taking calculated risks and making the needed investments to exploit opportunities and attain higher business value. Stresses the importance of following concurrent engineering practices to accelerate cycle times and reusing solution patterns in innovative ways. Captures best practice for innovation under speed duress and contains a broadly applicable checklist for managing projects.
Crowdsourcing and Its Impact on New Product Development	
Authors	Tim Gilchrist
Source	Microengagement, LLC
Summary	Crowdsourcing is the process of tapping previously unorganized and dispersed sources of knowledge from the general public. The confluence of communication technologies and social networking makes crowdsourcing product development incredibly profitable today. Traditional product development is comparatively slower, less dynamic, and less responsive to the needs of consumers. Crowdsourcing techniques can allow us to uncover the truth behind organizational needs and challenges.
Design Complex Adaptive Systems for Defence	
Authors	Anne-Marie Grisogono
Summary	In order to generate desired outcomes and to avoid undesirable side effects, defense systems in the future will have to be more agile and adaptive, as well as incorporate sufficient intelligence into their design to reduce the demands on human management since their complexity is arguably reached a level that is higher than our human ability to comprehend.
Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Life Cycle	
Authors	Ernst Frickle
Source	BMW-Munich
Summary	To yield great enhancements, flexibility, agility, robustness, and adaptability are four key aspects that need to be considered to incorporate changeability into system architecture. In order to stay ahead of competition in dynamic environments it is inevitable to ensure sustaining superior system capabilities and customized functionality and therefore three basic (ideality, independence, modularity) and six extending (integrability, autonomy, scalability, nonhierarchical integration, decentralization, redundancy) architectural principles support the implementation of the four key aspects and enable rapid responsiveness to emerging and changing markets as well as reduced lifecycle cost.
Detecting Network Vulnerabilities through Graph Theoretical Methods	
Authors	Patrick Cesarz
Source	Villanova University
Summary	The inhibiting bisecting problem is an effective method for determining network criticality as it pertains to power grids. The inhibiting bisecting problem, a graph theoretical formulation for identifying vulnerabilities of a network, aims to find loosely coupled sub-graphs with significant demand/supply mismatch. There are, however, limitations to this approach, because whereas it correctly generates the intended results, it also provides extraneous information.
Engineering Complex Systems with Models and Objects	
Authors	David W. Oliver
Source	Mcgraw Hill

Summary	In order to improve the sharing of ideas about complex systems across institutions and scientists, a systems engineering model, developed in the U.S., and Europe is used. In order to develop the best practices to use this model, the steps of the process must be clearly defined and an information model for each of those steps must be developed. The text serves as an introduction to modeling, and the application of modern object-oriented techniques and as a reference for more experienced users.
Formation of Machine Ground and Part Families in Cellular Manufacturing Systems Using a Correlation Analysis Approach	
Authors	Wafik Hachicha
Source	Munich Personl RePEc Archive
Summary	To formulate a multivariate approach based on the correlation analysis for solving the cell formulation problem is approached in three phases. In the first phase, the correlation matrix is used as similarity coefficient matrix. In the second phase, Principal Component Analysis (PCA) is applied to find the eigenvalues and eigenvectors on the correlation similarity matrix. In the third stage, an algorithm is improved to assign exceptional machines and exceptional parts using respectively angle measure and Euclidian distance. This approach is used because it has the flexibility to consider the number of cells as a dependent or independent variable.
Grand Challenges for Systems Engineering Research	
Authors	Roy S Kalawsky
Source	Loughborough University, Systems Eng Research 7th annual conf
Summary	The author presents five grand challenges for systems engineering research in the near future: 1) Ultra scalable Heterogeneous Systems, 2) Ultra scalable Autonomous Systems, 3) System Verification, Validation, and Assurance of Extremely Complex Systems, 4) Modeling & Simulation - Total System Representation and 5) Through Life Information and Knowledge Management.
Idealized Design: How Bell Labs Imagined – and Created – the Telephone System of the Future	
Authors	Russell > Ackoff, Jason Magidson, and Herbert J Addison
Source	Wharton School Publishing
Industry Recommendations for DoD Acquisition of Information Services and SOA Systems	
Authors	SOA Working Group
Source	Association for Enterprise Integration
Summary	Describes challenges associated with systems that are a mixture of services and procurement.
Integration of COTS: Curse of Blessing	
Authors	Mark Halverson
Source	INCOSE San Diego Presentation 26 April 2010
Summary	There are many potential advantages to a COTS based system and using a risk-based SE approach can help reap those benefits. Some disadvantages are: it is always a compromise between competing stakeholder needs, the marketplace and supplier retains ultimate control over the critical components of the systems, and the systems engineer will have to spend greater efforts in managing the procurement process, suppliers, and business environment. Develops the concept of a "glass box" for flexible interfaces, standards, and modeling. The case is made that knowledge of black box internals is necessary as we obtain increasingly complex systems.
Is a Unified Methodology for System-Level Design Possible?	
Authors	Alberto Sangiovanni-Vincentelli

Source	University of California, Berkeley
Summary	A unified system level design approach, developed at UC Berkeley, called Platform Based Design (PBD) is presented. PBD comprises a methodology enabling design reuse, early verification and analysis, virtual prototyping and automatic traversal of the design hierarchy from specification to implementation.
Manufacturing Cell Design: An Integer Programming Model Employing Genetic Algorithms	
Authors	Jeffery A Joines
Source	NSF
Summary	An integer programming formulation using a genetic algorithm is presented to assist in the design of cellular manufacturing systems. This integer-based approach allows the designer to incorporate or selectively move constraints on the number of permissible cells. Through experimentation, this approach was found to be an effective, as well as, flexible clustering technique. The further development of improved genetic operators and experimentation with parameter tuning during execution of the GA could lead to better solutions, improved performance, and a definitive stopping criterion.
Matrix Factorization Techniques for Recommender Systems	
Authors	Chris Volinsky
Source	Computer (IEEE) August 2009
Summary	Survey paper from Yahoo and AT&T on the most popular tools for recommender systems. Readable with limited mathematics.
Mixing Collaborative and Cognitive Filtering in Multiagent Systems	
Authors	Ramon Sanguesa
Source	University de Catalunya, Based Recommender Systems
Summary	The combined approach of cognitive and collaborative filtering may improve the usefulness of Recommender Systems. Describes the fully domain-independent ACE Multi-Agent System to emulate and simulate human cognition in a collaborative environment and expounds on its usefulness as a tool for leisure recommendations.
Model Based Integration and Experimentation of Information Fusion and C2 Systems	
Authors	Sandeep Neema, Ted Bapty, Zinofon Koutsoukos, Himanshu Neema, Janos Sztipanovits Gabor Karsai
Source	http://www.vuse.vanderbilt.edu/~koutsoxd/www/Publications/FUSION09_0506_FI.pdf
Summary	Modern Network Centric Operations drive the complexity of Information Fusion and Command and Control (C2) Systems. Driving this complexity further is the interplay dynamics of the human element, information systems, and communication networks. The lack of low-cost realistic experimental context limits the testing, evaluation, and further development of fusion systems to small-scale localized experiments.
Model Driven Development Needs More Than Product Models	
Authors	Barry Boehm
Source	USC-CSE Executive Workshop on MDA, March 16th, 2005
Summary	The paper discusses the difficulty in model integration and makes the case that “complete consistent" ontology is probably infeasible.
Modeling Approaches for Large-Scale Reconfigurable Systems	
Authors	Kwa-Sur Tam

Source	World Academy of Science, Engineering and Technology, Vol. 17, 2006
Summary	A tool that is used to model reconfigurable interdisciplinary complex systems (RICS) should be based on linear graph representation and support symbolic programming, functional programming, the development of non-causal models and the incorporation of decentralized approaches. Using an object-oriented approach, both the component models and the analytical functions can be organized into a hierarchy of generic classes from which domain-specific models and function classes can be created.
NP-Complete Problems and Physical Reality	
Authors	Scott Aaronson
Source	Scott Aaronson, Complexity Theory Col SIGACT News Mar 2005
Summary	Interesting study on the implications of embedded computing for Capability on Demand. Discusses the interplay between physical systems and optimization.
Open Innovation - Implications for S&T Organizations	
Authors	Dianna Wu
Source	Booz Allen Hamilton
Summary	An overview of open innovation models, tools for technology scouting, and a discussion on the implications for S&T organizations. Open innovation is an attempt to capture profitability alternative processes of innovation outside of the traditional organization environment. As relevant knowledge becomes more widely dispersed, investing in an open innovation network and outsourcing an organization's own activity will prove extremely valuable. Booz Allen's third party scouting and vetting can also be used as a crucial tool for efficiently identifying promising technologies.
Oral History Session (Interview of Dr Robert Frosch)	
Authors	David DeVorkin
Source	Interview of Dr Robert Frosch, Niels Bohr Library & Archives
Summary	A theoretical physicist by training (Ph.D. Columbia University 1952), he served as Director for Nuclear Test Detection and Deputy Director of the Advanced Research Projects Agency. The interview discusses the need for synthesis versus analysts and decomposes the problem we have managing complex systems to one of an over dominance of Hellenistic epistemology.
Profiling Complex Systems	
Authors	Renee Stevens
Source	SysCon 2008 IEEE International Systems Conference/MITRE
Summary	To achieve the overarching mission, systems-of-systems, enterprise systems, and even extended enterprise opportunities have been developed. In order to engineer this class of system, a process that demands consideration of increasing scale, the rapid pace of change of the underlying technologies, the complexity of system actions, and shared ownership and control must be taken into account. To profile complexity and uncertainty in large scale system engineering developments, a diagnostic tool is presented to propose an approach to tailoring engineering and acquisition strategies and practices to the specific circumstances at hand.
Ratio Hypergraph Partitioning using BDD Based MBOA Optimization Algorithm	
Authors	Joseph Schwarz
Source	BRNO University

Summary	This paper discusses algorithms for automatically decomposing a graph into sub-graphs with few interfaces. The authors then discuss how this may be used to design system decompositions.
Reverse Engineering of Biological Complexity	
Authors	Marie E. Csete
Source	Science
Summary	Engineering systems have started to have biological levels of complexity. This complexity is often hidden in the idealized laboratory setting and normal operation and only seen when contributing to rare cascading failures. Biology is the only science where feedback control and protocols play a dominant role and there are now enough examples for engineers and biologists to come together to close the loop of complex systems and eliminate specious theories.
Scientific Collaborations as Complex Adaptive Systems	
Authors	Phillip Anderson
Source	JSTOR
Summary	Scientific collaborations can be considered complex adaptive systems due to their counteracting forces – individuals, disciplines, and institutions - which dictate their behavior. Complexity theory can aid us in improving our understanding of scientific collaborations, boosting their efficiency, and helping them achieve an equilibrium state necessary for smooth project completion.
Service Oriented Manufacturing	
Authors	Mike McGrath
Source	Mitre SEPO Collaboration
Summary	A manufacturing service is defined as a service within the lifecycle of a manufactured product; that is, a service that contributes to the design, production, fielding, and/or support of that product. And Service Oriented Manufacturing (SOM) is defined as a paradigm for addressing the integration of manufacturing processes across the product life cycle both within a single firm and across the supply network. In order to support the development and deployment of a practical SOM, a service infrastructure is proposed that can exist within the parameters of traditional defense enterprises and will enhance the performance of existing manufacturing and product support teams by providing more flexibility, reducing risk, and improving supply chain security and trust.
SSE Research Focus Areas	
Authors	John Wade
Source	Stevens Institute of Technology
Summary	The presentation outlines the future focal points of the Stevens Institute of Technology School of Systems Enterprises: Cognitive Systems, Evolving Systems, Trusted Systems, Systems Engineering, and Workforce Development. They propose that a set of principles, a framework, and key concepts be developed for each focal point. This will create an infrastructure of tools for system simulation as well as a Trusted Systems Laboratory in which to experiment with actual systems.
Study of Naval Aviation Programs Sensor Procurement	
Authors	Dr David Smith
Source	Booz Allan Hamilton
Summary	A case study of the cost reduction when a common platform architecture is used for FLIR systems across Navy aircraft
System Security Engineering, Final Technical Report SERC-2010-TR-05	
Authors	Jennifer Bayuk

Source	Stevens Institute of Technology
Summary	Current systems security engineering is based on the flawed assumption that a system perimeter is bounded by technology and that COTS technology control measures can be configured to address adequately most security requirements. This research roadmap suggests a series of modules that take the best of current system security practices and integrates them with a systems thinking approach.
Systems-2020 Historical Lessons Learned	
Authors	Dr David Smith
Source	Booz Allen Hamilton
Summary	Historical survey of the need for CoD starting with WW2. Shows that red tape has been our bane for a very long time.
Technology Tools for Rapid Capability Fielding: Final Out Brief	
Authors	Jim Carlini et al.
Source	DDR&E Rapid Toolbox Study
Summary	Discussion of the need for CONOPS tools for improving acquisition QRC efforts.
Ten CAD Challenges	
Authors	David Kasik
Source	IEEE Computer Graphics and Applications
Summary	Without requiring disruptive discontinuity in skills and production, a radical evolution will come about with the next wave of CAD. With the changes that will come about with the use of CAD, using the order-of-magnitude (OOM) rule that says, which says: If anything changes by an order of magnitude along any dimension, it is no longer the same thing, offers a strategy to cause revolution in an evolutionary manner.
Terms of Reference - Defense Science Board (DSB) 2010 Summer Study on Enhancing Adaptability of our Military Forces	
Authors	Ashton Carter
Source	Memorandum for Chairman, Defense Science Board
Summary	Ashton Carter's view on adaptability and the DoD mandate, capturing the current (Apr. 12, 2010) state of thought within DoD

X. Appendix III: Qualitative Findings

This appendix shows a general summary of the findings obtained from interviewing the SMEs. The first table shown here is a summary of general themes, recommendations, or thoughts from these SMEs. The following tables within this appendix are summaries in a specific area, such as MBE, PBE, CoD, and TSD.

<table>
<tr><th>Theme</th><th>Supporting Data</th></tr>
<tr><td>Adaptability should be clearly defined</td><td>

There must be some type of internal yardstick within a system for adaptation to success. This yardstick is what changes are based. It is a measure of what's good and what's bad.
Anne-Marie Grisogono's team has developed a rigorous methodology / framework to identify the needs for being adaptive, how to be adaptive, the decision rules, etc. There are three dimensions of the framework:

1. What is the scale?
2. Classes: What kind of problem are you trying to deal with? There are five ways of dealing with problems:

A. Continuous improvement - we do this routinely. The other four deal with future stresses:
B. Responsiveness – immediate threats and opportunities that don't require you to change your fundamental approach
C. Resilience – loss of capability or threats of loss of capability
D. Agility – ability to maintain a helicopter view while pursuing a course of action…keep in mind the critical assumptions and monitor those assumptions to make sure they are valid
E. Flexibility – you don't know what you're going to have to deal with in the future. There are two ways to deal with this: (1) You improvise or (2) In the instance where you are dealing with a new demand / threat, you attempt to cobble something together that is new)

3. Levels: There are five levels of this third part of the framework.

Level 1: Sense the world – changing what you're doing from moment to moment based on the information you're receiving…not changing the capability. All other levels always work towards level 1.
Level 2: Improve the capability through adaptive processes - find a better of way of getting and analyzing information. The more uncertainty there is, the more likely it is that you need an adaptive approach. You need feedback to understand how to make it better. Adaptation in a sense is a calculated bet that the future will bear similarities to the past. An adaptive process is a closed loop. To work, it needs to be a cycle of information that rapidly moves
Level 3: Learning to learn – applying adaptation to it. We have many dysfunctional adaptive processes in place. Need a model that relates independent parameters to what they influence, towards the emergent properties of adaptation. Anne-Marie's team has the beginnings of a rigorous methodology for improving the ability to adaptive.
Level 4: Work on refining the internalized proxies – pleasure and pain drive decisions from moment to moment. How do we determine the internal yardstick for determining success and failure? Need to have multi-scale levels of success and failure. We don't ever develop them. Most

</td></tr>
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	performance metrics don't align with what actually matters. Systems are broken because you're using the wrong proxies and the incentives are messed up. The problem is it is difficult to come up with good proxies. Ideally your proxies are things that you can observe over a fast enough time scale. They should align with what will matter over the long term. ▪ Level 5: **How do you distribute roles and responsibilities for command and control between all of those systems?** Every design decision is actually a conjecture out of many possible conjectures about what would work. You need to expose those conjectures and ask yourself whether they matter - tuning the system of systems parameters.
Scalability is a key consideration	• Scale makes it difficult – because of the scale, interoperability is very difficult
	• Systems have to be trustable, interoperable, and scalable – For instance, say we're using algorithms for finding bad guys in traffic patterns of data –i.e. discovering connections. How do we extract more information from sensors? They may be useful for 10 users but in today's intelligence they have to be able to scale both in real time and for the sheer magnitude of data. The problem is facing trillions of nodes; it's 10 users verses 200,000 users.
	• M&S tools scale really well. They allow us to validate the performance at several levels. Allows conceptual development and performance evaluation before we even build engineering prototypes
Clearly defined standards are required	• Ultimately all organizations are local – and they tend not to be interoperable – and there's resistance to standards or resistance to adherence to standards. How do we get them to work together? ○ Aircraft Carriers – have good interoperability between their own task force - but when they run into another task force, they run into a different set of standards – there is resistance ○ <u>How do we push interoperability in standards at the lowest level?</u> How does the system designer operating in isolation design parts for a system with its own standards?
	• *There's a problem with standardizing across the government.* There really are commercial standards that have to be adopted or we won't get anywhere. We can't create our own. • Where there are shortcomings in the standards or tools – what we ought to be doing is studying those and trying to influence the community in whatever direction is beneficial.
Standard interfaces are required	• As you're able to link tools through information exchange and interoperability – you can use CATIA and M&S tools to do real analysis and validation. As long as we standardize these things in the Government – you're force multiplying your engineering staff – cutting dev time. ○ Standardizing interfaces and tools would force multiply. • We're a long way from that. We haven't been able to share those tools and interfaces. If you just look at the development timeline – and evaluation timeline – and how those would be simplified with standardization on this level. • When you start emphasizing modular and common standard interfaces – you can plug and play more often – as we've always wanted to do – build the hooks in for the answers we expect are coming.
	• The interface design is the only thing that makes the systems work. ○ The government has to work the interfaces to ensure that the due diligence in

	engineering is done way ahead of time – put the analytic rigor in the design of the interfaces and the components connecting to the interfaces. ◦ There has to be intense analytic rigor around the engineering of the interface and the definition of the number of components that describe the system.
	• Need to take incredibly complex systems and capture them in a way that makes them understandable or agile through standard interfaces. ◦ Example: The home theatre analogy – home theatres 40 years ago were an integrated cabinet with several components. It was a long wooden box with a 20-25" color TV – a record player – a tuner – in one integrated cabinet. • The impact on the market is that you have hundreds of players in the market – each company that focus on what they do very well. • You optimize your skills and abilities along what you know – Samsung with TVs – Sony with Blu-Rays – someone else will figure out the other parts – sounds, etc. Market built of specialists that somehow work together. • Part of it is because the consumer decides how and what we buy- don't bother selling to us if you don't do it the way we need it. ▪ Example: UAVs – UAVs are built – integrated top-to-bottom capabilities from the vehicle to the C2 platform. Has to interface with and enter the C4ISR continuum. Need a standardized uplink and downlink to integrate with other systems.
	• Need standard formats, need linkages to final specification
Environmental Challenges Impact the Ability to Have Agile / Adaptable, Complex Systems (Process)	• Challenges with system lifecycle design. ◦ DOD 5000 is asked to have a waterfall – starting to get milestones that are systems development milestones – milestones inherited from years ago from waterfall – whose objective is to get through a certain life gates – it is different than milestones that you'll get your through iterative or other lifecycles besides waterfall. ◦ Where is the systems engineering voice that says "hold on," what lifecycle do I want to extrude these contracts through and how do I get them working together to get through the initial milestones? It's not done. ◦ Another question I hear from INCOSE – "When are you guys going to finally do something that will contribute to the knowledge base of thought as to how you do lifecycle development?" ◦ Where is the lifecycle which takes into account the reality of the software development team will really produce the lifecycle – when are you going to give me a lifecycle in which the requirements base is going to change every three months? ◦ We aren't doing any of that. Since the acquisition lifecycle drives you through a set of risk gates – you have perhaps dozens of contracts – each one has different objectives. Different lifecycles – *so how do you do lifecycle integration?* • In the pre-milestone phase – why do you think if you can't integrate the major lifecycles – independent of requirements – the constructs that say how are we going to execute this job? Given the scope of the objective, the size of the task – there is nothing being done to the lifecycle to mitigate that objective.
	• Uncertainty factor in getting systems working – you don't know what you don't know – there's always going to be an uncertainty factor.

	○ Implement feedback methods to identify why costs went up, and then isolate and look at the initial estimate and variance in estimates as programs progress. This allows you to see if you have factors that regularly occur – or factors that might be "one offs" – the one offs may be your best target for risk mitigation. ○ Even though we have lessons learned we relearn the same lessons over and over again – we'd like to have a methodology or tool that consolidates these. • Would like to have a quantifiable knowledge vendor – something to get inputs and build a quantitative tool that correlate cost to delays and similar waste factors. • Need to empower program managers to run their programs and then hold them accountable. Too many PMs blame other people. They need to be empowered – and then they need to be held accountable – let them make decisions – and then hold them accountable – right now there's so many constraints on them it's nearly impossible to hold them accountable. I think that if you give a program manager a clear statement of what his system is supposed to do – and you give them the money to do it – a good PM can get the job done for you.
	• Policy documents have conflicting and/or overlapping requirements, DoDAF, DoD5000, and JCIDS. This hinders systems development. A typical acquisition program has to develop 50 documents [to meet requirements].
	• In the IC industry there is a design incentive for improvement while in the defense industry there is a fundamental reason to make design more effective • We need to change the market conditions to incentivize design efficiency • Indeed, current incentives are exactly wrong, especially for industry delivering systems to government.
Environmental Challenges Impact the Ability to Have Agile / Adaptable, Complex Systems (People)	• Need to improve the leadership skills of systems engineers ○ Many systems engineers think they are process stewards – good PMs and System Developers aren't given the authority, in many cases, to properly manage their programs and make the necessary big changes. *We should equip them with leadership skills.*
	• We need to improve the preparation (education) of engineers. The pool of engineers needs to be renewed, especially to refill the ranks of management personnel that understand the engineering issues • In trying to implement any changes top level management and technical people need BOTH be involved. There are examples that show that when one or the other group is not involved, results of the efforts of those involved are easily nullified.
	• One area that is very important is Leadership. If DoD is going to do research for SE study, What are the leadership dimensions in the future for areas such as program strategy and process management? How to develop the right kind of people for the future?
Environmental Challenges Impact the Ability to Have Agile / Adaptable, Complex Systems	• Optimization of the Contractors – Oversell the government on what they can do to win the contract – then ramp up "large standing armies of engineers" to work these programs – and believe that they will solve technical problems faster than they do. The Govt. is paying for large standing armies while they are trying to work through the initial technical problems. Program ends up delayed because they have trouble meeting technical challenges before the program can ramp up.
	• Program runs out of control because the contractor low-balled
	• Contractors Liar's Dice – competitive Liar's Dice game has to be defeated. FCS was a ton

(Contractors)	of promises and no delivery. ◦ System promotes and even participates in *optimistic technology projection. "Setting the mark high" is used as an excuse to not do technology due diligence.* ◦ Leads to program slips, increased costs, etc. ◦ Contractor over promises – Examples: Ceramic armors = next big thing – promises made by industry and materials scientists who didn't understand the armor design problems (just materials). ◦ You don't start a full-up systems program with unproven technologies – if you want to achieve those sorts of development times you have to have proven technologies that are understood – and that limits your accelerating of advanced capabilities – makes it more evolutionary
Environmental Challenges Impact the Ability to Have Agile / Adaptable, Complex Systems (Customer)	• The Soldier is the biggest complex system issue. Materiel questions – If I had to answer the questioned unrestrained – it is the soldier (and his/her equipment) - We're in a period where the threat is not massed systems, but counterinsurgency, working within civilian populations. ◦ Soldiers carrying 150-200lbs of equipment – loading them down with electronics – night vision – power considerations – water and supply – protection issues. Filled with constraints. Now you're also asking them to *operate in complex social-cultural environments.* And you're asking them to *operate complex systems*. Add emotional stress, physical stress, and today that system is much more fragile in many ways. ◦ Not to be glib. Standard systems and mathematical systems questions don't apply to the solider system – might be outside of the comfort zone. ◦ Systems challenges in reducing power weight, and space requirements.
Technology / Tools / Approaches to Examine Further	• Introduce people from outside of systems design/engineering to come and participate in the process
	• Autonomous manufacturing that makes the systems engineering process more interdisciplinary.
	• A tool that expanded the estimates (cost, schedule) – Just like you have a system of systems, you should have a tool of tools – You have scheduling/cost tools now, which may or may not be great. Can we take the working elements of these to a systems level and find new ways to find unknowns and risks – have a tool of tools – integrate these systems, and integrate the various risks at a system of systems level.
	• Need to evaluate schedule and cost risks in a systems of systems approach. FCS is an example – I doubt we did that. I'd strongly urge DDRE look at FCS as an example of where system of systems went wrong – were there individual tools that could have helped do prediction on risks. And then were they integrated at a systems of systems level? • In other words, you may have lessons learned at a lower level (i.e. on a predator system, for example), but were they communicated when examining risk at a higher (System of Systems) level? I would like to see a tool where all of these lessons learned and best practices are communicated across the system of systems.
	• **Improving Acquisition Lifecycle:** We have to do things smarter – we can't just say the acquisition is not the right way – we just need to do it smarter – with modular/ open systems. – and incremental capability. Instead of developing long cycle programs that go 15 years. We have to chop our programs down into 5 years chunks – constrain our vision that acquisition cycle is the same as the technology cycle. The dev cycle is longer

	than the tech cycle – constrain our vision that such that our dev cycle is the same length and our technology cycle.
	• Develop a Design Structure Matrix - displaying relationships and understanding complexity of relationships – could work with anything including standardization to understand the way things interact.
	• Market mechanisms – Create markets for services. Data services, processing services. Another form of social networking? ○ Example: Futures Market for intelligence analysts to share their conclusions – doesn't share methodology, but will share conclusions and lessons learned. Rely on futures – a way of expressing opinions safely – if the market prices moved around, others could read data into it. ○ Key to the endeavor is that individual contributors would have a stake in the game – real money – essentially spending next year's budget.
	• Leverage Social Networking tools – for sure – Gen Cartwright proved effectiveness when he ran staff on his blog a few years ago

Model-Based Engineering	
Theme	Supporting Data
Need for increased collaboration and involvement from stakeholders	• Let the user build the model so that he/she's part of the defining process. • Bringing the end user into the process avoids the mismatch between the system that's finally developed and the purpose for which it's developed. • The relationship of the user to the system with the exception of the user interface – incorporating the user early on – interdisciplinary. • You're going to develop a cockpit – an ejection seat – ergonomics – triggers –etc. Allow the pilot to sit there and make sure that it all functions properly.
	• We really need to address the issue of being able to engage the end user in the development in a continuous way. • *Engaging the end user* – we have a lab at MITRE called Agile Capability – its physical lab but it's also distributed – it's a creative environment with toys, models – things to play with for conceptual development. But you have to bring everyone to the facility. How can we engage the end user so that we can do this conceptual conversation with the end user in a more tailored way.- with whatever resources they have on hand (ex: just a laptop)?
	• Solution is to have a way to assess requirements with functionality with cost. For example have simulation tools (via GUI's) that allows the user to get involved early in the design process (again functionality requirements and cost). This was user soon realize which requirements are really not needed
Need virtual environments	• In a previous study I did – we pointed out the use of virtual environments for SE. Especially in the upfront portion of design – the concept engineering – there's a lot of tech in the gaming and virtual environment world.

	• For instance - used for training and mission rehearsal. Very little application at the front end of the process. If you try to design a system that has interaction with a user then you should be able to immerse the user in that environment. • You don't have to go through the prototyping – you can let them play with it in and give feed back in a virtual environment.
	• If there were a smart way to understand all of the external interfaces, how they relate to each other, and the dependencies on other programs and where they are in their development – that would be significant.
Requirements Communication Challenges	• The developers don't always understand what the user needs – and they can't iterate it well across those worlds. • It's the way the design is captured in a model – in many ways. To capture engineering design in a model-based format vs. standard document. • DoD does little MBE and we haven't fully embraced MBE in our normal design processes. There are different camps in development and some are skeptical.
	• Work on the concept of Requirements translation. Many problems can be traced to the representation and translation of requirements. Text descriptions of requirements tend to be interpreted in varying ways, and thus a formal process is needed to specify design requirements.
	• There is some mistrust between the acquisition community and the end users based on experience with the requirements process as well as languishing programs (i.e. over budget, late delivery). Addressing this necessitates having a requirements process that is flexible with:
	• Ability between a program manager and the user/user community to trade requirements based on impact. • An iterative process. "We may not be able to give you what you want on the first pass, but we can make it happen on the next pass."
System Integration Challenges	• System Integration – is obviously a major issue – a lot of money spent on the integration phase in SoS –It's a highly unpredictable point in the life of a systems development. One area where model- based methods could have a huge impact. My feeling is that DoD could take a topic like this and create programs with assured effectiveness of model based technology in solving really hard SI issues. • The SI systems at Vanderbilt - ~100 people working with Boeing and SAIC – the META program of the FCS program. I believe that we showed was a unique way of using MBE in integrating large scale systems. ○ Using models of components. If you model the interfaces precisely – the behavior of the components have greater fidelity in the model – if you reintegrate the system you can spot the tough problems and help the whole program buy down the risk quite a bit. • Meta-modeling – you use single state flow for modeling individual components – take the models and integrate them to simulate the integrated behavior of the

	systems – these modeling methods come together to form a concept of Meta-modeling. ○ The modeling tools tend to be too self-contained – you are encapsulated in their modeling environment – In a SOS – you need a model at several levels with different tools, integrated with the heterogeneous models
Tool Interoperability Challenges	• Obviously, the vendors really want to lock you into using their model. What else locks you in using more than their modeling concepts? You're expending your intellectual assets on their model – and locked into their proprietary model. ○ You have a suite of models – can't change it for other applications – because of the specifics of the modeling language. • Domain-Specific Modeling Language (DSML) – Adjust your modeling language – the abstractions in the modeling language – to the problems you want to attack – the fundamental problem is how to rapidly change in an agile and evolving modeling environment. • The solution is called Meta-programmable modeling tools – you model the modeling language. Much narrower concept – you model the semantics. Two suites that are meta-programmable – it turns itself into a totally domain-specific modeling environment – uses domain-specific model elements that are defined in the meta-programming model. • You can create a model management environment – so that they don't need to be dedicated to one particular modeling paradigm. One of the earliest – and mature is the Model Integrated Computing Tool Suite – has been used and actively used in the FCS program. It's a very successful part of the FCS
Lack of Trust in Simulation Results	• One of the big challenges is trust. Non-simulation people don't really trust simulation results. They are OK with it for training, doctrine development, etc. but it is difficult to get them to accept M&S T&E for example. That is changing, mostly driven by cost containment than a real appreciation of M&S. Related to this is culture. If you are old enough, think back to the transition from drafting board to CAD. Took years. In part the tools needed to mature, in part related to retraining but in part to shifting the design culture. M&S has the same issues. It's easy to say 'create tools like RW so any engineer can create their own simulation, but then the engineer needs to understand the power and the limitations of simulation. • One way I have proposed in the past to work on this would be to run a simulation design effort in parallel with an actual development. It would fail of course, recognizing that up front is important (!), the goal is to stress the tools and the processes. Such an effort would help everyone understand the strengths/weaknesses and thus would give you better insight into how to use simulation or what advances need be made
Modeling Doesn't Account for the	• Brute Force Statistical Testing vs. Design of Experiments • With Brute Force Statistical Testing – which (I think) is the norm for the Department – you're testing at 1, 2, 3 and up to 10, to test (x, y). Testing at 1 and

Extremes	testing 2, 3, up to 10. Do 10 conditions/tests (or however many variable you have) – and you can draw a statistical line. • Suggestion: Design of Experiments Testing – Tests the extremes. Take .1 and 10 – and if it's a multidimensional sort of thing, then you could do the corners of a cube and a middle point. You essentially draw your statistical line from the extremes • We were supposed to do DOE approach on SDB2 – but they didn't properly develop models up front – so they ended up basically doing a Brute Force approach • Modeling – need data to verify and validate models. Upfront verification might be more intensive than a single Brute Force approach at first – but you don't have to interrogate over and over again. • Programs shy away because early money is tough to get – but early validation ultimately saves budget and schedule overall. • MDA makes progress in this area out of necessity – because of the obvious constraints on missile testing – they cannot test the way the department does with brute force testing – You don't want to have real ballistic missiles coming in! Hard to develop statistical models because there's not enough actual data. MDA might be a pathfinder for showing modeling based acquisition because they are forced to model so much. MDA has done a lot of physics based approaches – developed sophisticated models – then done point data tests.

	• The central blind-spot is that the simulation isn't a good strategy for studying architecture, corner points (extremes), or security.
	• Gives you typical behavior – doesn't account for the extremes.
	  ○ Example: Digital Hardware Design (DHD): they no longer rely on simulation they rely on practical formal methods instead. Once you move away from digital hardware design – those methods in DHD – they don't scale to other design environments.
	  ○ So they do make a good study for how those methods can be applied at a larger scale.
	• They don't help with the extreme risks as well (as practical engineering and prototyping). Beyond their nominal function, they are really good at getting through a demo.
	• Bad at unintended consequences: Models are not good at sorting out the unintended consequences. Preparing for those unintended consequences is essential to 'getting there' ok.

Technology / Tools / Approaches to Examine Further	• MBE: integrate CAD tools with gaming and virtual environments. Tools that allow design teams to walk through a virtual environment and go. Have a single digital thread from concept to manufacturing - integrated with CAD and other tools – manufacturing and the like. There are different communities across the design chain – Systems 2020 should look across all of those and find ways to connect those digitally over time.
	• Look at DOORS (Dynamic Object Oriented Requirements System); it was bought by

	IBM [IBM website identifies Rational DOORS – a requirements management tool for systems and advanced IT applications - and Telelogic DOORS]. DOORS is for millions of line items. It is object oriented: requirements are handled as discrete objects
	• Look at CORE - the company that developed it has been bought by Vitech [CORE Model-Based Systems Engineering Software]. CORE is for thousands of lines of items.
	• Look at CATIA (mentioned multiple times)
	• Invest in a better framework to analyze and model at the system level and know co-dependencies and critical components. Gave the story of the "Lithium Anode Problem", the Lithium battery performance was being limited by the Anode, but so much investment still went to the cathode, cathode performance was improving 50% every 2 years vs. anode performance increasing 10% every 6 years. The investment in the cathode did not make sense from a systems perspective
	• Examine tools that allow people to build their own simulations. Create simulations that can create simulations. For example consider what was created by RealWorld (DARPA program), this program created a tool that took data from NGA (National Geo-Spatial Intelligence Agency) and allow you to create buildings and other landscapes. In general to create game like programs (simulations) that enable rapid mission rehearsal. This is an example of tools that create simulations. This is not the norm but it needs to be the norm. This is further reinforced by the fact that cost and time are overriding factors in creating simulations.
	• Object Process Methodology
	• Invest in Meta-programmable model based systems engineering. Invest in the sense that the existing tool suites need to be transferred exhaustibly. Programs that simulate that transition to applying meta-programmable modeling tools. And there is a whole category of these meta-programmable tools like: model transformers, model-based system integration tools – essential for the future.
	• Build mathematical models with different levels of abstraction (develop the concept of Platform Based System design). The model is different than that of the virtual machine levels in computer science, in that the specifications and requirements at each level need to be represented at all layers above, and in that the notion is a far more dynamic and continuous stratification of layers. See his published literature.

Platform-Based Engineering	
Theme	**Supporting Data**
Lack of Understanding of	• There are fundamental flaws in IT, for example, but you struggle to find a clear articulation of what those are even among the most sophisticated thinkers in the internet community.

the Tradeoffs at the Architecture Levels	• It's not impossible, but IT is treated like gravity – it's just there to be built on - it has become the platform – if you go and take a CS course, you don't learn networking fundamentals, you learn about TCP/IP. • This illustrates that we have tools for PBE but we do not have a foundational theory. It would be a little bit like we had ways of hacking together airplanes but we didn't know about lift/drag/propulsion. • The real problem is we have many interesting case studies - we have many good tools, but we lack a foundational understanding of what the architecture is. TCP/IP is the case study for this issue.
Technology / Tools / Approaches to Examine Further	• Don't re-invent the wheel, identify where modularity can come in across a broad portfolio of needs and have one platform that can serve them all. This involves knowing what you have and what your needs are across the board. ○ How? Establish a comprehensive database and characterization of components across the DoD and finding out where redundancy exists and where modularity can come in, in the procurement process and this can drive specifications with a common set of needs to all platforms.

Capability On Demand	
Theme	**Supporting Data**
Lack of Requirements to Fight Irregular Warfare	• The Capability based Req process is new. We lost track of our enemy – during the cold war we had a cohesive threat – now we don't know where the next enemy is lurking. There's no singular set of requirements that allows us to fight asymmetric or irregular warfare. Investing in the ability to be as agile as possible and quickly adjust to whatever the new thing is that we're facing is crucial.
Need to Find Ways to Repurpose What We Already Have	• One of the things we need to do is reinvent inventing. In other words, we ought to develop a capability to take in-hand technologies and reshape them quickly. And that takes some of the development time out of the equations. ○ Smarter system of repurposing. If we're going to go build a new ship – perhaps we ought to think of it as a low-cost platform and – in every other regard it's designed for the most flexibility for incorporating new components wherever you want. Rearming - with missiles, bombs and so forth – you have an affordable platform and you can produce 150-200 a year. Building that flexibility in from the beginning is important for the tactical challenges we're facing.
	• Composable Capability on Demand – focus on the rapid integration, adaptation, reconfiguration of capabilities in near real-time. Deliver something to the end user so they can configure and adapt on the fly. What kind of environment is needed to do this? Special education? How do you deliver a capability and make sure it's assured? How do you build them in a way that they can be composed in the field in that way?
	• Need to have the ability to reuse both existing tools and existing standards. There is a lot that can be done with common sense and the best way to solve the problem may be highly specific to it.
	• Need to leverage existing components better

	• Need to have good and efficient ways of determining critical and non-critical system components, it is not worth investing in over-engineering non-critical components • As sophistication in components increases (integrated circuits smaller dimensions/higher density transistors, etc.) manufacturing has a hard time following it. Must decide whether it is necessary to use the most sophisticated components, or scale back a few years to be good enough: "There is no point in making an AND gate perfect if you've got 10^8 AND gates and the aggregate performance of the system is not predicated on a perfect AND gate." • As sophistication increases, lead time to market increases, this leads to entry of counterfeit components into the market (see article in Electronic Engineering Times, May 10, 2010, examples were GPS frequency standard oscillators, NAVY Radar components, microprocessor and nonvolatile RAM for F-15 and others). • DoD typically values performance over delivery time "Why can a small company get a computer from chip to product in 4 months ready for Christmas, but DoD can't?" – The extra performance may not be worth it if the reliability is compromised, particularly by the increased probability of counterfeit subsystem components
Need to Improve DoD Design Philosophy	• It's more of a design philosophy and acquisition philosophy – how do we acquire things and what can we level on them? There's a business side to COD that the DOD doesn't use. You want to decouple very clear modules. • In general – everything goes through a prime that controls everything – COD is in many ways more of a price and acquisition issue as opposed to an engineering issue.
Technology / Tools / Approaches to Examine Further	• Invest in tech scouting and prediction tools to imagine capability ahead of time, in this sense capability on demand could be predicted by a good enough understanding of the evolution of COTS components
	• Dynamic Adaptability – automated systems that can gather data at the time it needs it – and then switch the capabilities out on its own to adapt reality. This is going to be incredibly important going forward. ○ We used to do sensing independent of the application. Now we need to merge Sensing -> Decision into one capability so you sense and decide in one move.

Trusted Systems Design	
Theme	**Supporting Data**
Need to Improve Reuse	• Need to leverage existing components better • Need to have good and efficient ways of determining critical and non-critical system components, it is not worth investing in over-engineering non-critical components • As sophistication in components increases (integrated circuits smaller dimensions/higher density transistors, etc.) manufacturing has a hard time following it. Must decide whether it is necessary to use the most sophisticated components, or scale back a few years to be good enough: "There is no point

	in making an AND gate perfect if you've got 10^8 AND gates and the aggregate performance of the system is not predicated on a perfect AND gate." • As sophistication increases, lead time to market increases, this leads to entry of counterfeit components into the market (see article in Electronic Engineering Times, May 10, 2010, examples were GPS frequency standard oscillators, NAVY Radar components, microprocessor and nonvolatile RAM for F-15 and others). • DoD typically values performance over delivery time "Why can a small company get a computer from chip to product in 4 months ready for Christmas, but DoD can't?" – The extra performance may not be worth it if the reliability is compromised, particularly by the increased probability of counterfeit subsystem components • Need to find a way to reuse components and have a thorough characterization of critical and non-critical system components, along with better models to predict how they interact, Trust/Assurance analysis should be increased vs. investing in making perfect subsystems • Characterize what you have and how it works (make a database?) • Establish better testing and standardization protocols, COTS subsystems should be leveraged as time to market and cost may be more important than performance, in order to ensure Reliability, Interoperability and Trust of COTS sub-systems, or any other subsystem, it is critical that better rapid testing and diagnostic protocols and/or technologies be established • Complex systems research may also help TSD in being able to identify rapidly the critical components

Technology / Tools / Approaches to Examine Further	• Anti-Tamper – really needs to move forward. Need to make sure that the chip set can't be tampered with.
	  ○ When I was at Raytheon we developed a chipset – amd flame-spayed it – the GPS receiver essentially allowed the DoD to turn off / turn on – etc the GPS in devices we sold to outside the country. In the early days we could only give the correlator chips to certain people – we had to be very careful
	  ○ Now the trick is to develop a system can adapt to the threat – it can't be tampered with.
	  ○ With this we have the ability to involve other nations. Through selective availability of these Anti-Spoofing Modules – by them signing on – there are joined to us in a security sense. I don't have to worry that tech falls into the wrong hands because it's in their best interest to protect it – and the technology adapts to tampering from outside.

XI. Appendix IV: Additional Supporting Data

Date	Event (Nation Targeted)	Threat	Systems Stressed	Counter	Threat Warning	Comments
2001	Hart bid contamination (U.S.)	Bio-weapon	Air Filtration, perimeter security	Gas decon	decades	Bio-weapons have been a threat since WW2
2002	Cult Group Falon Gong disable satellite (China)	Electronic attack	Broadcast satellite systems	Adaptive canceler	decades	U.S. critical coms systems include robust ECM
2003	OIF air strikes (U.S.)	IAD Systems	Strike aircraft	Stealth	decades	Soviet air defense led to U.S. Stealth…
2004	Hezbollah Attack (Israel)	Katyusha rocket	Air Defenses	Patriot	years	…also a Cold War development
2005	Iraq Insurgents (U.S.)	>40 Deaths/month	Convoys, HMMWV	Armor, intel	months	IED was unanticipated
2007	Chinese missile shoots down test satellite (U.S.)	ASAT Weapons	PC Computers	MEO, GEO	days	US ASAT weapons
2007	Russia Attacks (Estonia)	Cyber weapons	National infrastructure	Scanners, networks, monitors	hours	U.S. Lagging vastly in Cyber
2008	15M servers attacked (global)	Conflicker worm	Computer servers		none	Zero day theats are recurring theme with cyber weapons
2009	Predator feeds hacked (U.S.)	Targeting exposed	TST strike group	Encrypt		
2010	Google suffers Large Scale Chinese Cyber Attack(global)	Botnets, polymorphic viruses	Sudanese Human rights group	ongoing		

Table 3: Timeline for recent attacks, or threats. Shown is the year of the event, the nature of the threat, the victim, countermeasures employed and warning. For the Falon Gong satellite jamming we deem the solution to be available, since our military systems routinely hardened. This does not imply that commercial systems don't remain vulnerable

During the course of this study, an effort was made to characterize the attributes of adaptable complex systems. The following key characteristics emerged in interviews with subject matter experts and literature research:

- heirarchy - the division of complex systems into more manageable components, subsystems, or structures
- incorporation of standards and interfaces
- design reuse **-** the incorporation of engineering practices such as PBE, product lines, etc.
- consideration of human factors
- **supremacy** - the ability to successfully meet requirements or perform the desired task or function

As an example of a complex, adaptable system consider a competitive smartphone (e.g. an iPhone, Droid, or Blackberry). These cellular technologies have incorporated all of the key characteristics of adapatability with significant degrees of success.

Figure 12 shows a notional evaluation of a fighter jet, complex vehicle, ISR sensor, intelligence fusion application, and computer network attack / defense / exploitation (CNA/D/E) tool in terms of these key characteristics of adaptability. In the figure, the scale for successful incorporation of a characteristic ranges from 0 to 5 where 0 represents no incorporation and 5 represents maximum incorporation. The notional fighter jet, for example, achieves maximum rating in supremacy of design, human factors, and hierarchy, but scores very poorly in design reuse and incorporation of interfaces and standards.

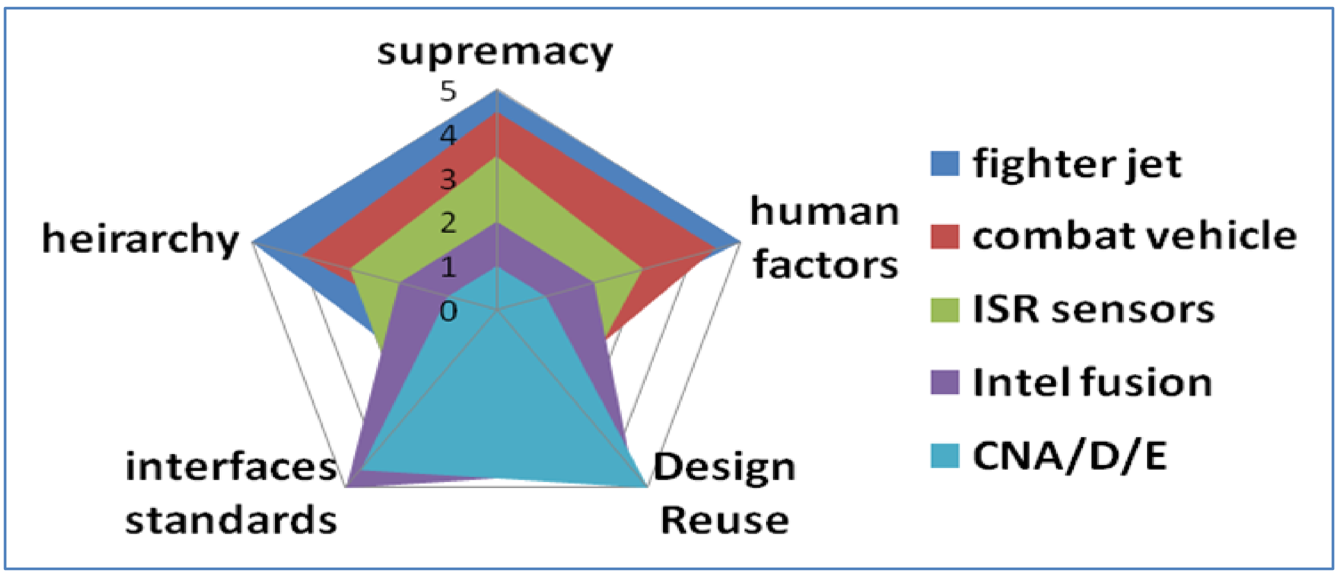

Figure 12: Notional Evaluation

XII. Appendix V: Complexity: How do we measure it?

The Systems 2020 initiative was designed by Director, Defense Research and Engineering (DDR&E) to provide leadership to the DoD science and technology (S&T) community in addressing the growing complexity of major DoD acquisition systems, with a focus on systems agility. As an example of this consider Figure XX below. This chart shows the difficulty level of modeling a variety of academic, defense, and commercial systems. The x-axis represents the number of components within the system and the y-axis represents the difficulty level of modeling the system. Compare the difficulty of developing modeling tools for a missile v. human cognition, for example. A missile may consist of hundreds or a thousand components with relatively well understood physics behind the component interactions, environment, and trajectory to assist in development of models. By contrast, human cognition may consist of 10^{15} or 10^{18} components with relatively little understanding of the science or physics behind the process to assist in model development. As DoD systems expand into areas of greater complexity, new system engineering tools and practices must be incorporated to manage complexity in light of competing desirable attributes such as flexibility, adaptability, and cost efficiency. Here we will discuss current usage of the term complexity within the systems engineering community and clarify the definition for the purposes of this study.

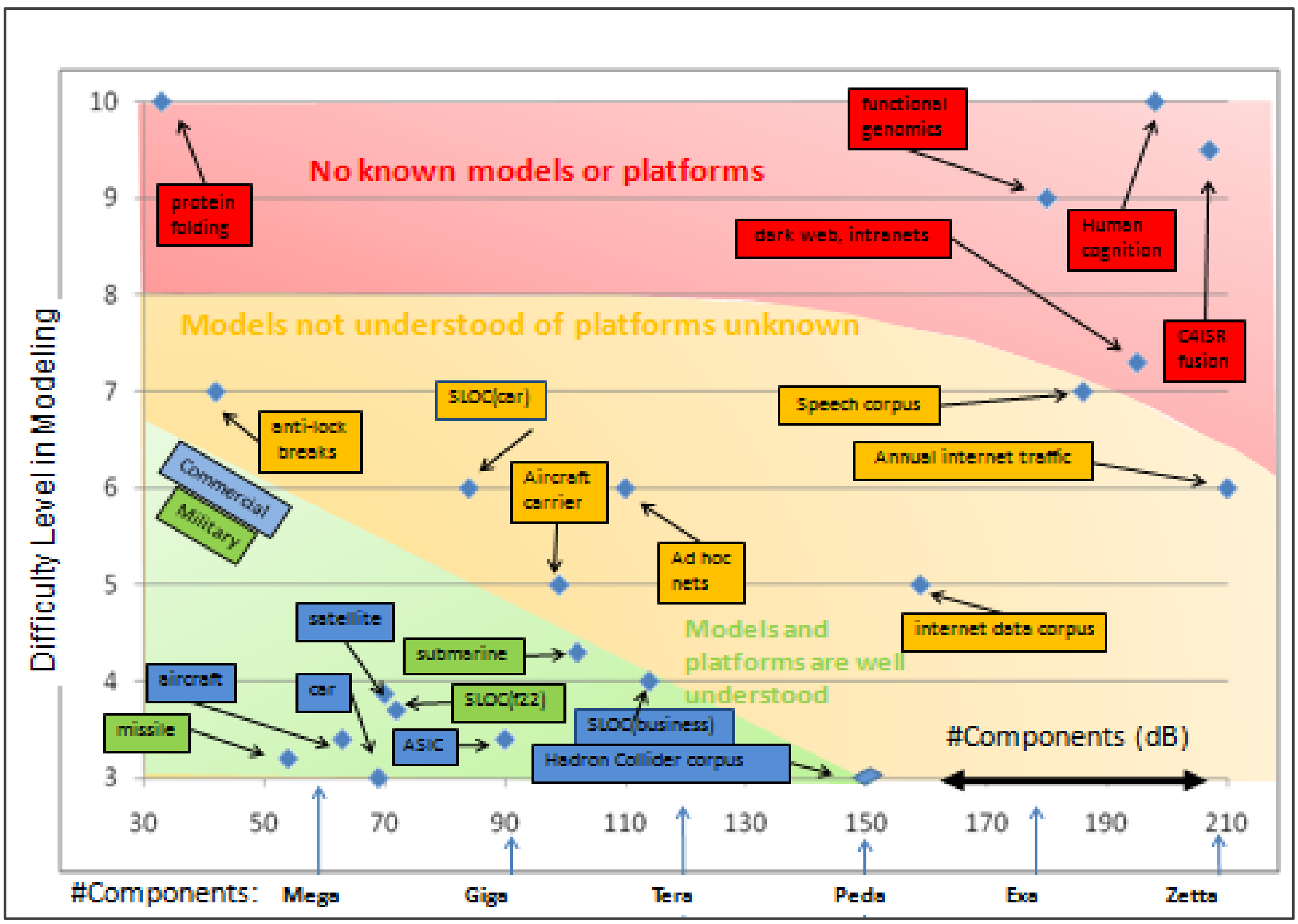

Figure 13: A notional evaluation of a fighter jet, combat vehicle, ISR sensor, intelligence fusion application, and computer network attack / deception / exploitation tool in terms of the key characteristics of adaptability.

For this study, we have defined complexity as “the degree of difficulty in accurately predicting the behavior of a system." In the text below we will seek to obtain a clear understanding of the concept of complexity and its current usage within the systems engineering community.

Systems engineers generally refer to system complexity as a cumulative concept incorporating the sum of the complexity of individual components, the complexity of links between system component, and the complexity of functions or tasks performed. Complexity occurs in a variety of contexts and phrases including the complexity of system architecture, system design, and overall technical complexity, as well as complexity in requirements, mission, and organizational partnerships. Tools to reduce or manage complexity in system engineering include modularity, application of hierarchy in system design, and informed architectural decisions during the early phases of system design.

Joel Moses presents the commonly referenced definition of complexity below in his working paper, "Complexity and Flexibility."

> There are many definitions of complexity. Some emphasize the complexity of the behavior of a system. We tend to emphasize the internal structure of a system. Thus our approach is closer to a dictionary definition of 'complicated'. A system is complicated when it is composed of many parts interconnected in intricate ways. Let us ignore the near circularity of the definition. The definition points out two features of the concept. It has to do with interconnections between parts of a system, and it has to do with the nature of these interconnections (their intricateness). One can use information theory to get at the notion of intricateness in the sense that a highly intricate set of interconnections contains much information, whereas a highly regular one contains far less. For our purposes a simpler definition will be helpful. We shall define the complexity of a system simply as the number of interconnections between the parts.

Several efforts are underway to define complexity as a metric that can provide system engineers and decision makers with quantitative feedback in examining system architectures. A general framework has been defined mathematically for expressing complexity as a sum of constituent parts.[24] In the aerospace field, AFRL's INVENT program defined complexity as "equivalent to the inflexibility of a design to meet future growth requirements"[25] In yet a third metric, Jones et al define complexity for large scale defense systems as equivalent to the RDT&E cost driven by the number of nodes and links within the system.[26] Further research in this area may be of interest to DDR&E and the Systems 2020 initiative as well formulated metrics for complexity provide system engineers with tools to engineer increasingly complex systems with greater speed and efficiency.

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[24] Reference "Abstraction Based Complexity Management", Overview p. 2, Paul Eremenko, DARPA TTO

[25] Walters, E. A., and Iden, S., "INVENT Modeling, Simulation, Analysis and Optimization", AIAA Aerospace Sciences Meeting, Orlando, FL, 2010-287.

[26] Jones, R., Hardin, P., and Irvine, A., "Simple Parametric Model for Estimating Development (RDT&E) Cost", 2009 ISPA/SCEA Joint Conference.